REPORT SD-TR-86-83

Radar Cross Section Measurements

Prepared by

R. B. DYBDAL
Electronics Research Laboratory
Laboratory Operations
The Aerospace Corporation
El Segundo, CA 90245

30 September 1986

Prepared for

SPACE DIVISION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
Los Angeles, CA 90009-2960

APPROVED FOR PUBLIC RELEASE
DISTRIBUTION UNLIMITED

This report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract No. F04701-85-C-0086 with the Space Division, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009-2960. It was reviewed and approved for The Aerospace Corporation by M. J. Daugherty, Director, Electronics Research Laboratory.

Lt Wesley R. Dotts/CGX was the Air Force project officer.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Wesley R. Dotts

WESLEY R. DOTTS, Lt, USAF
MOIE Project Officer
SD/CGX

Joseph Hess

JOSEPH HESS, GM-15
Director, AFSTC West Coast Office
AFSTC/WCO OL-AB

DISCLAIMER NOTICE

THIS DOCUMENT IS BEST QUALITY PRACTICABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SD-TR-86-83	2. GOVT ACCESSION NO. AD A180040	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) RADAR CROSS SECTION MEASUREMENTS		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER TR-0086(6925-05)-5
7. AUTHOR(s) Robert B. Dybdal		8. CONTRACT OR GRANT NUMBER(s) F04701-85-C-0086
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Aerospace Corporation El Segundo, CA 90245		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Space Division Los Angeles Air Force Station Los Angeles CA 90009		12. REPORT DATE 30 September 1986
		13. NUMBER OF PAGES 67
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Radar cross section	Bistatic systems	Coherent repeaters
RCS measurements	CW radars	Instrumentation radar
RCS prediction	Anechoic chambers	High resolution radars
Monostatic systems	Compact ranges	RF measurement accuracy

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Progress in radar cross section measurements is strongly related to the progress in radar technology. Recent acceleration in radar technology and processing techniques has generated a corresponding acceleration in interest for radar cross section measurements. Historically, early radar cross section measurements were performed to determine the detection range of radar systems, a fundamental objective that still exists. Later measurements, coupled with analytic techniques and computer codes, were

Abst. F

DD FORM 1473 (FACSIMILE)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

performed to extend our understanding of the radar scattering process. At the present time, the availability of broadband electronics, signal processing techniques, and digital technology results in radar cross section measurement programs which are directed toward exploring the performance of operational waveforms and processing, target discrimination, target detectability in clutter, and radar scattering control.

The fundamentals of radar cross section measurements are reviewed. Measurement facilities, including the present research activities on compact range techniques, are then described. Instrumentation radars have benefited from both wide bandwidth electronics and digital processing capabilities. Fourier transform techniques, in particular, provide both additional information on target scattering, and increased measurement accuracy by isolating the target from radar returns from the measurement facility. The frequency coverage has also been extended to include millimeter wave frequencies. Achievable accuracy is important in any measurement program, and those factors that limit the accuracy of radar cross section measurements are discussed.

CONTENTS

FIGURES

I. INTRODUCTION

Measurement techniques for the RCS (radar cross section) of a target are closely mirrored by the progress in radar system development. The infancy of RCS measurements dates to World War II (Ref. 1), when the target's RCS level was required to determine the detection performance of early radar systems. While this fundamental objective is still required today, the narrow bandwidth waveforms of the early radar systems have been displaced by the wider bandwidth waveforms used in today's systems. Detection performance for today's waveforms has extended RCS instrumentation requirements beyond the early CW RCS measurements. Further experimental work continued after the initial measurements and, in concert with analytic efforts, deepened our understanding of scattering mechanisms. Predictive techniques are now available for a broad class of target geometries.

Both experimental and analytical techniques have benefited greatly from digital processing techniques, and instrumentation as well has benefited from recent advances in solid state technology. The initial, fundamental objective for RCS measurements is now extended to include demonstrating techniques to distinguish different types of targets, modifying target scattering properties, separating targets from background clutter, and determining the response of targets to today's radar waveforms and processing.

The interest in RCS and its measurement was highlighted in a special issue of the IEEE Proceedings in August 1965. This special issue reviewed analytic techniques for RCS prediction, measurement and facility techniques as represented by the state of the art existing at that time. In the twenty years since that publication, computer codes have been developed for RCS prediction, advances in broadband, solid state electronics have extended both instrumentation and operational radar performance, and digital processing techniques have had a profound influence on the volume of data processing and the resolution of target features. These factors have expanded our understanding of, and ability to examine, the details of the scattering process.

RCS measurements are closely allied with the measurement of antennas. In both cases the measurement response versus the aspect angle is determined. The power received or transmitted by the terminals of the antenna is measured, and the transfer of power between an incident field and a field scattered by a radar target is also measured. The concepts of far field conditions, polarization, etc are common to both antenna and RCS measurements. Likewise, instrumentation and test facilities for antenna and RCS measurements are interrelated. Antenna measurements have been more recently reviewed (Ref. 2), and detailed standards for antenna measurements have been published (Ref. 3). RCS measurement principles discussed in earlier work (Ref. 4) remain valid, as do descriptions of the analytic techniques, measured data, and measurement techniques discussed in the Radar Cross Section Handbook (Ref. 5). Recent progress is built on this rich heritage which is well worth reviewing. Present measurement programs are driven by today's radar technology, which increases the resolution of individual target features, uses fundamental mechanisms to control the target RCS, and expands the frequency coverage to include microwave and millimeter wave frequencies. This paper reviews RCS measurement fundamentals and discusses both progress to date and trends of measurement programs.

RCS measurement programs must carefully consider the objectives of both the experiments and the operational applications. Several fundamental considerations, e.g., far field, polarization, instrumentation sensitivity, and range facility requirements, are basic to program planning. In the past most measurements dealt with the response of an isolated target that was measured in a facility that strived to provide a free space background. At present, interest in target detection in an operational environment has increased and the scope of some measurement programs has expanded to include radar detection for a target embedded in a surrounding clutter environment with the dynamics of the relative target and radar motion. In such cases, the target, clutter background, and operational dynamics must be simulated; this type of measurement is referred to as "dynamic," as opposed to the "static" measurement of an isolated target. The recent progress in radar technology and processing techniques also expands the requirements for instrumentation

and processing beyond what was adequate in the past. Specialized instrumentation, signal processing techniques, and test facilities are required to evaluate the salient features of the radar waveform and its processing. Thus, a determination of the measurement's scope is fundamental to the design of a measurement program.

The fundamental considerations and definitions associated with RCS measurements are reviewed in Section II. Different types of measurement facilities are reviewed in Section III. Instrumentation radar requirements and designs are reviewed in Section IV. Measurement accuracy, important in any experimental program, is discussed in Section V.

II. FUNDAMENTAL CONSIDERATIONS

The definition and underlying assumptions for RCS are fundamental to measurements. The response of the radar target is profoundly influenced by the operating frequency, the target orientation relative to the radar system, and the radar waveform and processing. Polarization plays an important role in RCS characteristics; in recent years, polarization processing techniques have been developed to discriminate targets from the surrounding clutter background (Ref. 6). Dimensional scaling techniques have long been applied to RCS measurements (Ref. 1). Scale models are more manageable during measurements and the increased frequency also reduces the required size of the measurement facility. These subjects are reviewed in turn.

A. DEFINITIONS

A basic definition of the RCS of a target is

$$\sigma = \lim_{R \to \infty} \frac{4\pi R^2 \times \text{power density in scattered field}}{\text{power density of incident plane wave}} \tag{1}$$

where σ is the symbol traditionally used to denote RCS and R is the range separation between the target and the radar receiver. The incident plane wave excites currents in the target which reradiate in a scattered spherical wave. The geometry associated with this definition is given in Fig. 1. The incident plane wave from the radar arrives from a specified aspect associated with a coordinate system fixed to the target, denoted by θ and ϕ in Fig. 1, and a scattered spherical wave component is received by the radar at an aspect similarly defined by that coordinate system. It should be emphasized that the "spherical wave component" directed towards the radar receiver is not isotropic, but varies with target geometry, operating frequency, aspect angle, etc. The definition of RCS is fixed to a coordinate system embedded in the target. The incident radar illumination and the scattered signal measured by the radar receiver are expressed by the angular coordinates of this target-associated coordinate system.

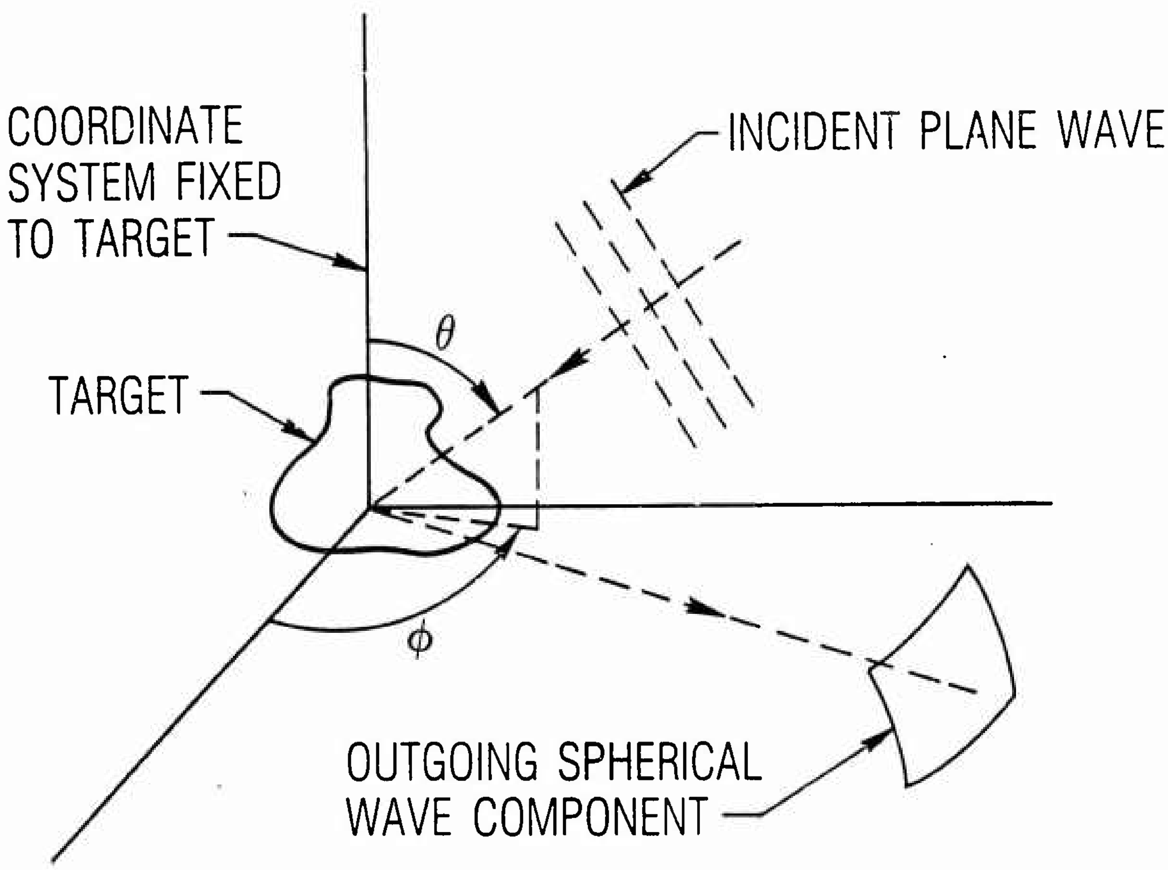


Figure 1. Target Geometry for RCS Measurements

The RCS definition further distinguishes between monostatic and bistatic systems. Many radar systems collocate the transmitter and receiver; in this case the aspect angles relative to the target are identical for both the radar transmitter and receiver, and the corresponding RCS is referred to as monostatic. When the transmitter and receiver are not collocated, the aspect angles relative to the target are different, and the RCS is referred to as bistatic. Bistatic radar designs have been considered in recent years for a variety of reasons, and increased understanding of the bistatic response of radar targets will be derived in future studies. Monostatic RCS requires the specification of two angular coordinates, and bistatic RCS requires the specification of four.

Far field conditions are implicit in the RCS definition. The target must be sufficiently separated from the radar so that the incident energy is "plane" over the complete target. Similarly, the radar receiver must be sufficiently removed from the target to measure the outgoing spherical wave component. The scattered wave must also be "plane" over the radar receiving antenna. The essence of the RCS definition concerns the transfer of power from the incident plane wave into an outgoing spherical wave component. The currents induced by the incident plane wave's illumination reradiate like the antenna radiation mechanisms. The far field conditions for RCS thus have commonality with antenna measurements. The RCS definition also assumes a target isolated in free space and does not include multipath interaction with or scattering from the surrounding background. Like the far field characteristics of an antenna, the far field RCS of a target does not vary with changes in range. This property has a practical application. When far field conditions are to be validated or when potential multipath interaction is present, the measurements can be repeated at different range distances. Valid measurements are indicated by identical results for the different range values; moreover, the repetition of measurements results in greater confidence in measurement accuracy.

The dimension of RCS is area, which has led to the terms "echo area," "effective area of the target," etc., which have been used synonymously with RCS in the past. In a manner similar to antenna gain, which is referenced to

a fictitious isotropic level, RCS is commonly referred to a one square meter area, and dBsm (dB relative to one square meter) expresses the target level logarithmically relative to a square meter area. For measurements of targets which are dimensionally scaled, a convenient reference area is the square of the operating wavelength, λ, and the target level, σ/λ^2, can be expressed in terms of dB-λ^2 (dB relative to a one square wavelength area) in this case.

While the dimensions of RCS are area, it is important to recognize that RCS has no general relationship to the physical area of the target. The RCS of a target depends on the target's geometry, its material properties, its orientation relative to the radar, the radar frequency and waveform, and the incident and received polarization. These factors must be carefully specified to make the data meaningful.

B. RADAR WAVEFORM

In the past the bulk of RCS measurements were made with narrow bandwidth CW waveforms. Such measurements sufficiently characterize the target's response to narrow bandwidth waveforms or validate analytic models of the target scattering. In recent years operational radar systems which use broad bandwidth waveforms have been developed. This trend results from the availability of wideband electronics, the reduced vulnerability to electronic countermeasures, the decorrelation of clutter returns, tracking errors, etc, the desire to separate closely spaced targets, and the increase in target information that results from high resolution waveforms. Accordingly, the target's response to illumination and processing with high resolution waveforms needs to be determined. The more general terms "radar waveform" and "target response" are used to denote both the power relationship in the definition of RCS and the target information that can be derived from processing the waveform.

The RCS of a target significantly depends on the radar frequency. The frequency dependence of a given target undergoes wide variations even if the radar orientation remains fixed. The low frequency scattering mechanism is the excitation of dipole moments by the incident plane wave. These dipole moments depend on the volume of the target, and the scattering is not strongly

influenced by the details of the target's geometry. At high frequencies the incident plane wave excites currents on the target's surfaces, and the response is significantly influenced by the details of the target structure. Moreover, the radar response of a target depends not only on the transmitted waveform, but also on the processing performed by the radar receiver. For example, a wide bandwidth waveform may be processed to achieve a high resolution response, or the wide bandwidth may be simply used for diversity benefits (described in Section IV). The frequency dependence of the target and the effects of radar processing must be recognized in the specification of a measurement program.

The CW measurement of target RCS simplifies instrumentation radar requirements. Wideband radar measurements result in more complex instrumentation radar requirements, and the trends of present day radar technology and processing capabilities lead toward the exploitation of the benefits of wideband response. The amplitude and phase response of the target RCS can be measured over a bandwidth and combined with the spectral characteristics of the radar waveform to assess the detection performance of a given radar system against a given target. In the laboratory this approach is encouraged by the present commercial availability of network analyzers having significant processing capability. At the same time, the availability of wideband solid state electronics and digital processing technology encourages the development of specialized instrumentation that can replicate the operational waveform and its processing. This latter approach is particularly appealing when the measurements are made on a dynamic basis. For example, when doppler processing is to be exploited, an instrumentation radar with the operational waveform is coupled with simulated motion dynamics to provide a realistic assessment of operational radar performance which is unattainable by other means. In this case different portions of the target may have different doppler rates, which can be observed by doppler processing.

C. POLARIZATION REQUIREMENTS

The polarization properties of the target RCS are another important parameter. The polarization of both the incident plane wave and the scattered

spherical wave must be specified. The importance of polarization is highlighted by recent efforts (Ref. 6) to separate targets from surrounding background clutter by polarization discrimination techniques. In the future more emphasis on the polarization properties of radar targets can be anticipated. The definitions of polarization for the incident and scattered wave components follow those used by the antenna community. These definitions and techniques for their measurement are described in detail in Ref. 3. Two linearly independent, orthogonal polarization states are required to specify an arbitrary polarization. Target RCS values are generally referenced to ideal linearly or circularly polarized components associated with both the incident and scattered waves.

RCS polarization characteristics are defined in terms of principal and cross polarization components. The principal polarization component results from target scattering that does not depolarize the incident field, while the cross polarization component results from target depolarization. Target characteristics which depolarize the incident field include lack of symmetry, target roughness, and material properties. If linear polarization components are denoted by "h" and "v" for horizontal and vertical, respectively, the principal polarization components are denoted by σ_{hv} and σ_{vv} and the cross polarization is denoted by σ_{hv} and σ_{vh}. The first subscript specifies the polarization of the received spherical wave, and the second subscript specifies the polarization of the incident plane wave. Similarly, if "r" and "l" denote the right and left hand circular polarization components, σ_{rl} and σ_{lr} are the principal polarization components and σ_{rr} and σ_{ll} are the cross polarization components. The principal circular components are σ_{rl} and σ_{lr} because the handedness of circular polarization is reversed upon reflection from a planar conductor.

Scattering matrix techniques may be used to transform RCS values in one polarization state to another; e.g., linear polarization measurements can be transformed into circular polarization values and vice versa (Ref. 5, p. 20). The original work on scattering matrix transformations for the polarization properties of radar targets was done by Kennaugh; his work has recently been collected and republished (Ref. 7). Application of the scattering matrix

requires amplitude and relative phase measurements of target RCS. Bistatic RCS measurements require the amplitudes of the two principal and two cross polarized components and the three relative phase measurements between these components. Monostatic measurements reduce these seven independent measurements to five as a consequence of reciprocity. The application of scattering matrix polarization transformations requires a significant volume of data. The accuracy of the polarization transformation depends on the amplitude and phase measurement accuracy, which becomes particularly troublesome for low RCS levels. A second source of error results from the lack of polarization purity in the radar's antennas (Ref. 8). Redundant measurements of the polarization components are highly recommended to establish the credibility of the polarization transformation process.

The polarization properties of rotationally symmetric targets viewed along the axis of symmetry are a special case that provides a practical check of measurement accuracy. In this special case, depolarization does not occur because the symmetry of the object dictates a symmetric current distribution incapable of generating a depolarized response. Moreover, the target's rotational symmetry demands insensitivity to the polarization alignment. RCS measurements in this case should have a null in the cross polarized responses, σ_{vv} should equal σ_{hh}, and σ_{rl} should equal σ_{lr}. Verification that measured data on rotationally symmetric targets viewed along the axis of symmetry fulfills these conditions provides added confidence in measurement accuracy.

D. FAR FIELD REQUIREMENTS

The basic definition of RCS in Eq. (1) specifies plane wave illumination of the target and measurement of the scattered spherical wave by the radar receiving antenna under far field conditions. Thus, (1) the target must be in the far field of the transmitting radar antenna, (2) the radar receiving antenna must be in the far field of the spherical wave scattered by the target, and (3) the target must be in the far field of the receiving antenna. The conventional far field criterion, $2D^2/\lambda$ where D is the maximum target or antenna dimension and λ is the operating wavelength, is derived from the phase curvature of spherical waves. The peak phase error of a spherical wave

sampled over a dimension D on a planar surface located a distance $2D^2/\lambda$ from the phase center of the spherical wave is 22 1/2°. Far field requirements for RCS measurements are discussed in Ref. 9 and typical values are given in Fig. 2. Large targets measured at high frequencies result in excessive range requirements. Target scaling can be effective in reducing the required range.

The low frequency measurement of electrically small targets results in a second far field criterion. The scattering mechanism for this case is the excitation of dipole moments. When low frequency measurements are made, the power transfer can be distorted by mutual coupling effects between the radar antennas and the target. Thus, a second criterion for far field conditions, which becomes the limiting factor at low frequencies, is that the range separation between the antennas and the target must exceed several wavelengths to avoid mutual coupling errors. Figure 2 presents typical values for a 10 λ separation.

Physically long targets result in another inaccuracy even though the above far field criteria are satisfied. In this case, the space loss ($1/R^2$) from an incident spherical wave varies along the length of the target. For example, a 5 ft long target at 1 GHz requires 50 ft to satisfy the $2D^2/\lambda$ range; this range provides a separation of 50 λ. However, a 5 foot change in a 50 ft range results in a 1 dB amplitude change in the space loss for the incident field. Similarly, the reradiation from scattering centers that have different locations along the target length have different space loss values with respect to the radar receiver. At an infinite range, the space loss for each of these scattered field components has the same value; however, at a finite range, the space loss can differ between returns from individual scattering centers. If the target length is L and the range is R, the value of $((R+L)/R)^2$ should closely approximate unity to avoid these errors.

E. TARGET DIMENSIONAL SCALING

Dimensional scaling reduces the physical target size to more manageable dimensions for handling during measurements and reduces the required far field range. Dimensional scaling is based on the Theorem of Similitude (Ref. 10). When applied to RCS measurements, the theorem states that if the target

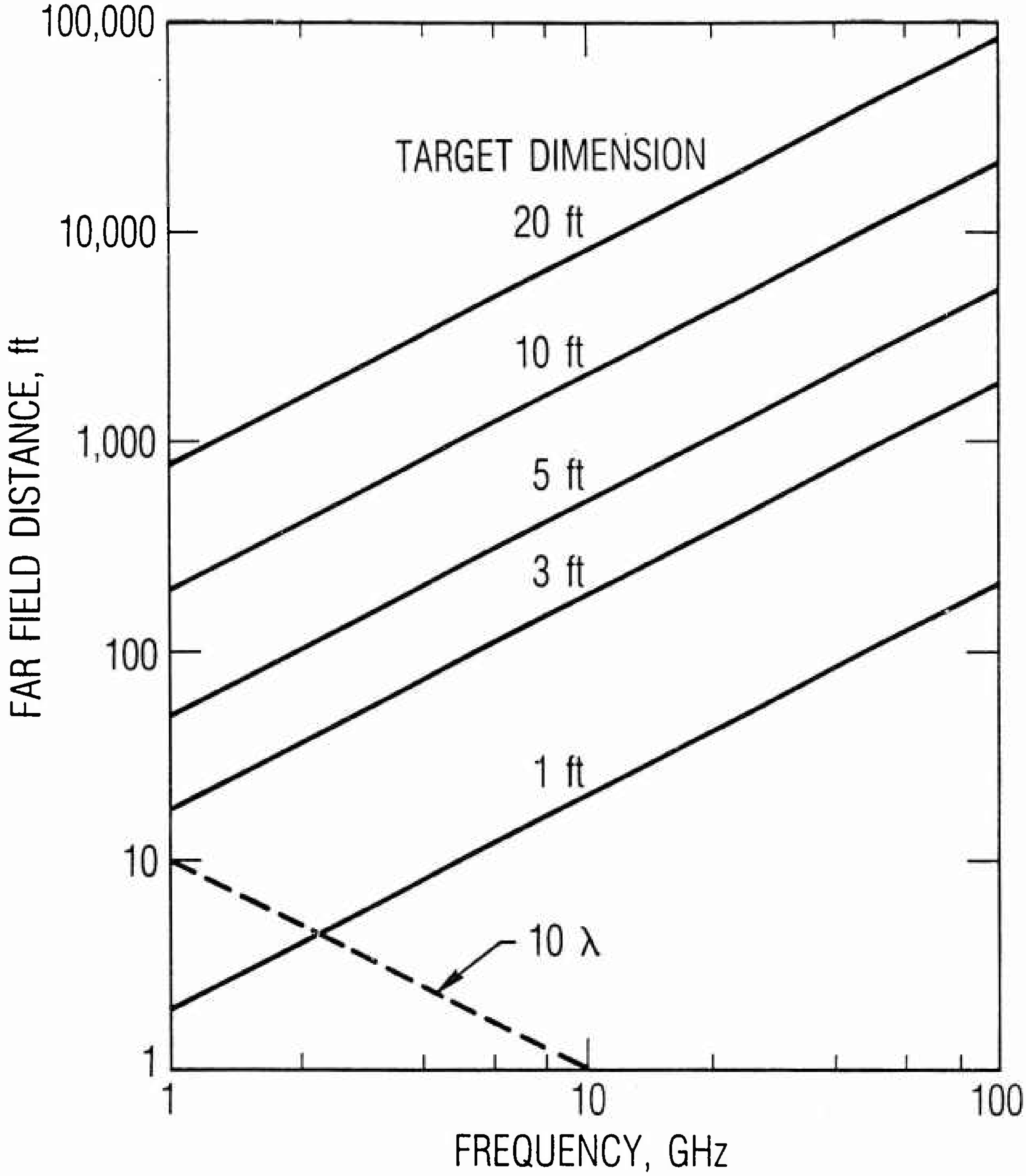


Figure 2. Far Field Range Requirements

dimensions in wavelengths, real and imaginary values of permittivity and permeability, and impedance remain fixed with frequency scaling, the value of σ/λ^2 also remains fixed. This invariance of σ/λ^2 results in its popularity in expressing RCS for scaled measurements. If the scaled frequency is k times the full scale frequency, the far field distance required for the measurement is reduced by k, an attractive feature in the measurement of large targets.

While the principles of frequency scaling are straightforward, questions concerning its application typically arise. If the target response is sensitive to the permittivity and permeability of materials, particular care must be exercised to duplicate the imaginary part of these quantities at the scaled frequency. Dimensional tolerances produce further uncertainties. If the dimensional tolerances and the statistics of their distribution for the full sized target are reduced by the scale factor, the scaling is exact. However, the duplication of the scaled tolerances places excessive burdens on model fabrication. If the target is smooth, duplication of the target dimensions to a tolerance of a sixteenth of a wavelength at the scaled frequency is generally accepted as accurate. Despite these questions of scaling exactness, scaling is widely used and is an extremely attractive means to facilitate model handling and reduce far field range requirements.

Target scaling does introduce a potential loss in the dynamic range of the measurement. When the target size is reduced by a factor of k, the absolute RCS level at the scaled frequency is reduced by a factor of k^2. If the background RCS contributions from the facility are independent of frequency, then the dynamic range of the measurement is reduced. However, the background RCS levels are frequency dependent; moreover, increasing the frequency by a factor of k provides greater opportunity to reduce the effect of background errors because the radar instrumentation has greater processing capability at the higher frequency. These factors need to be examined for each specific measurement application to assure an adequate dynamic range for scaled measurements.

III. MEASUREMENT FACILITIES

A variety of RCS measurement facilities have been developed. Outdoor ranges and indoor anechoic chambers have been widely used for the past four decades; these facilities are sized by the far field requirements of spherical waves. Compact ranges have been developed more recently and use near field focusing techniques to generate and process the incident and scattered wave components at a short range separation. Specialized facilities, e.g., transmission line ranges (Ref. 11) for the measurement of small targets, have also been developed. RCS facilities can also be used for antenna measurements and are described for that application in Ref. 3. The facilities mentioned heretofore strive to isolate the target in a free space environment, and the measurements are performed on a static basis. Dynamic measurements have been used in the past primarily to measure large targets under far field conditions. In recent years, a significant amount of sensor evaluation has been conducted with targets in an operational environment; these evaluation programs also provide the opportunity to gather RCS data on the targets as a secondary objective.

In addition to the measurement facility per se, target support systems and calibration techniques are also required. Target support systems must provide adequate, secure target positioning in the facility, and must present a very low level radar return. The target support system must also rotate the target so that different target aspect angles can be measured. RCS measurements not only require the determination of the relative radar return but also must be referenced to an absolute level; calibration standards provide this absolute level. Finally, techniques to evaluate measurement facilities will be described.

A. RANGE GEOMETRIES

The selection of a range geometry involves both technical and economic issues. Like many situations, no one facility type offers universally advantageous features; the requirements for each measurement application must be weighed against the specific attributes of each facility. In general, outdoor

facilities are used to measure large targets and are advantageous for bistatic RCS measurements. Indoor anechoic chambers are more suitable for the measurement of small targets and provide shelter from the wind and weather as well as privacy. Both outdoor ranges and anechoic chambers are limited by conventional far field conditions and their maximum usable range dictates the maximum target dimension at a given radar frequency. Compact range designs are actively being developed, and have been demonstrated at microwave and millimeter wave frequencies where the near field focusing is achieved with structures of reasonable physical size. Finally, dynamic measurements include target motion in the measured radar response and can provide a clutter background to determine the target detectability performance of a given sensor design.

1. Outdoor Ranges

Outdoor ranges are used for RCS measurements of large targets at range distances that would be impractical to enclose with a physical structure. A principal disadvantage of such facilities lies with their sensitivity to inclement weather and wind conditions. Outdoor ranges unavoidably interact with the surrounding terrain. This interaction has been treated by two approaches; one approach attempts to minimize ground reflections, while the second approach attempts to add ground reflections coherently to the direct path. In both cases, scattering from the surrounding terrain features and other reflection sources such as buildings must be controlled.

Several techniques to minimize ground reflections are available. The choice of siting can be effectively used, e.g., the instrumentation radar can be separated from the target by a valley. A pulsed mode can be used with the instrumentation radar to time gate out multipath returns. Similarly, modern network analyzer techniques use transform techniques in conjunction with windowing, and serve to isolate the target from the surrounding background. At higher frequencies, passive sidelobe control techniques can minimize the illumination of the surrounding terrain. Multipath components are reduced when the reflecting surfaces are sufficiently rough (Ref. 12); low vegetation appropriately placed can effectively diffuse and absorb multipath.

Diffraction fences have also been used to control multipath but their effectiveness is limited when diffraction from the tops of the fences is significant.

The second approach for outdoor ranges attempts to coherently combine the multipath components with the direct path signal. The terrain between the radar and the target is made as flat, conductive, and smooth as possible; therefore, this range geometry is referred to as a ground plane range. The radar antenna height above the ground plane is adjusted to combine the direct and reflected components coherently. At large ranges, the incident and reflected components coalesce with appropriate antenna illumination. This geometry can be interpreted in terms of image theory with the antenna height adjustment being equivalent to phasing the image and real antennas. The most widely known ground plane range is the RAT SCAT facility (Ref. 13). This facility is located on a gypsum flat, and the extensive real estate available at that location results in the capability to measure very large targets.

The design issues for outdoor facilities center on the control of reflections from the surrounding terrain. These facilities require careful attention to qualify the individual sources of reflection. Ground plane ranges require the additional effort to combine the reflected wave coherently with the direct path.

2. Anechoic Chambers

Anechoic chambers are indoor facilities whose walls are lined with absorbing material to simulate free space conditions. These facilities offer the attractive advantage of being independent of weather conditions. Many different types of facilities have been constructed and have had a long history of operation. A historical perspective of microwave absorber development and anechoic chambers may be found in Ref. 14.

Anechoic chambers can be further divided into two types of geometries. Rectangular rooms lined with absorber material are historically the first type of facility used for such measurements. Tapered chamber designs evolved at a later time and offer better performance at low frequencies. In a rectangular chamber, energy can bounce from the side walls, floor, and ceiling to create

multipath components. The degree to which this energy can be controlled depends on the directivity that can be achieved from the instrumentation radar antennas and the reflectivity performance of the absorber at the incidence angle. The tapered chamber evolved from an analogy with the radiation mechanisms of a horn antenna excited in its dominant mode. The tapered design reduces the multipath excitation at lower frequencies where the directivity of the instrumentation radar antennas cannot be easily achieved. An alternative rationale for a tapered design can be developed from a ray picture of the propagation within anechoic chambers (Ref. 3, p.31).

Anechoic chambers can be operated over a broad frequency range through careful design and the selection of absorber material. An example of this broadband capability is given in Ref. 15. This tapered chamber design has operated from 100 MHz to 93 GHz. The background RCS levels and reflectivity performance for antenna measurements are given in Fig. 3. These levels are obtained for CW operation and do not include the benefits of time gating or transform techniques.

The design issues for anechoic chambers center on the satisfaction of the far field criteria, which dictates the overall length, and the frequency range, which dictates the requirements for the absorber material. The choice between tapered and rectangular geometries depends on the anticipated need for low frequency measurements. At high frequencies, the interaction with the chamber walls can be controlled by the radar's antenna directivity, and rectangular and tapered chambers have comparable performance. The back wall of the chamber also involves some tradeoffs. One approach is to have the capability to tilt the back wall to reduce its background contributions (Ref. 15); this technique is effective for narrow band applications. The importance of the back wall contributions also depends on the instrumentation radar's processing capabilities. Background returns from the back wall can be eliminated by pulsed systems or by the windowing techniques used in modern network analyzers.

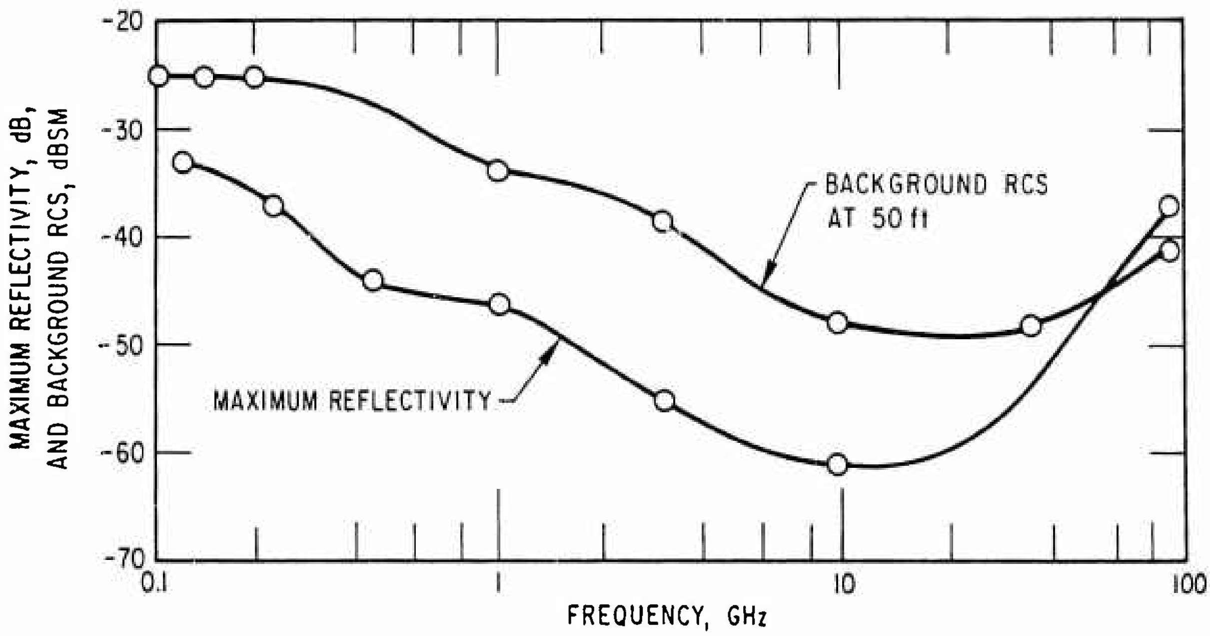


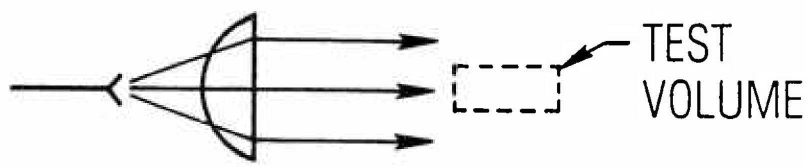
Figure 3. Background RCS and Antenna Reflectivity Levels of The Aerospace Corporation 90 ft Anechoic Chamber

3. Compact Range Designs

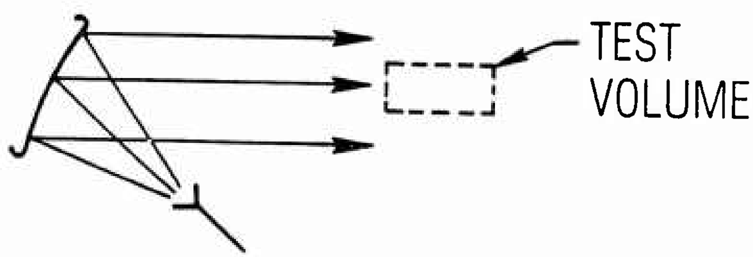
The overall size of outdoor ranges and anechoic chambers is based on the far field requirements for RCS measurements coupled with the frequency of operation and target size anticipated. In contrast with these facilities, the compact range uses near field focusing techniques to generate and process the incident illumination and scattered waves. The compact range thus evolved from the desire to reduce the range requirements dictated by far field requirements. The development of compact range facilities and techniques for their operation are actively being pursued at present.

Historically, dielectric lenses were used to reduce the far field range by correcting the quadratic phase variation which results in the near field (Refs. 9 and 16). More recently, compact ranges have used the plane wave generated in the near field of offset reflectors (Ref. 17). The two geometries are pictured in Fig. 4. In both designs, the required plane wave illumination of the target is obtained in the collimated near field of the antenna which would be formed by the lens or offset reflector.

Compact ranges have both lower and upper frequency limitations. The lower frequency limitation results from the inability to achieve the required focusing and from an increase in edge diffraction effects. The upper frequency limitation results from the phase perturbations caused by manufacturing tolerances. Present indoor compact ranges are limited to microwave and millimeter wavelength frequencies. Practical lens designs are limited by the required volume of homogeneous dielectric material and the reflection interactions between the lens surfaces. The offset reflector designs require a precise reflector surface for operation at high frequencies and are limited by the depolarization inherent in offset reflector designs (Refs. 18 and 19). In both designs the illumination must be controlled to obtain a uniform field over the test region, and edge diffraction must be avoided. In the offset reflector design, the reflector edges have been serrated (Ref. 20) or rounded (Ref. 21) to reduce their diffraction distortion of the desired plane wave illumination.



(a) Lens Geometry



(b) Offset Reflector Geometry

Figure 4. Compact Range Geometries

Several research directions are presently being pursued to develop compact ranges further. Improved feed designs for compact ranges (Ref. 22) control edge diffraction and improve illumination; broadband designs will be required to match the capabilities of available instrumentation. Dual reflector designs (Refs. 23 and 24) are being developed to increase polarization purity. Axial defocusing techniques (Ref. 25) can generate the phase curvature required of near field RCS measurements; this technique has potential application in dynamically evaluating glint errors in tracking systems by moving the feed along the feed axis to simulate range changes. Glint is a near field scattering phenomenon that results from the phase variations between the component scattering centers of the target and an approaching tracking radar (Ref. 26). These phase variations shift the apparent target location, and the resulting glint errors become the predominant tracking error when the radar is close to the target. These ongoing research efforts indicate the present, active development interest.

The design issues for compact range facilities center on the frequency coverage, control of edge diffraction, and uniform illumination in the target region. A low frequency limit results from the inability to achieve the required focusing and the edge diffraction effects. A high frequency limit also results from the manufacturing tolerances and their resulting phase perturbations. At present a commercial version based on the offset reflector geometry is available. Further development of this type of facility can be anticipated in the future.

4. Dynamic Measurements

A fourth "measurement facility" for dynamic measurements consists of the natural background surrounding the target. Two situations exist. In the first, the measurement program has the fundamental objective of gathering RCS data. The radar is typically fixed in location and the target motion results in a changing aspect angle over which RCS data are gathered; the measurement of an aircraft in flight is an example and its flight plan is carefully selected to obtain the desired data. A dynamic measurement may be the only feasible way to satisfy the far field criteria and, indeed, the earliest

measurements of aircraft and ship targets (Ref. 27) were obtained in that manner. In the second situation, RCS data are derived as a secondary objective of the measurement program. Many recent measurement programs have been conducted to evaluate sensor system detection of targets in an operational background. The target is typically fixed or slowly moving, and the radar is approaching the target. In these programs, the main objectives may be to quantify target detection performance or tracking accuracy to evaluate the sensor design. However, the opportunity to collect RCS data as a secondary objective exists; in general, such programs require further calibration to obtain useful RCS data.

The first situation imposes somewhat more burden than a static measurement program. A suitable instrumentation radar is required to provide not only adequate detection performance but also a target tracking capability; such instrumentation radars are generally more expensive than those used in static measurements. The target tracking must be performed in both the angular and range coordinates. Angle tracking is required to avoid pointing loss errors in the RCS measurement. Range tracking is required to compensate space loss variations that occur during the measurements. Finally, techniques for establishing and maintaining the radar system's calibration need to be implemented. These additional issues for dynamic measurements increase the complexity compared to static measurements and also increase measurement program costs.

The second dynamic measurement situation adds to the above burdens. These programs typically locate the target in a clutter background, and the RCS characteristics of the target must then be separated from the clutter background contributions. Such measurement programs should provide independent radar systems to establish the clutter background levels and assure that the clutter background remains unchanged during the course of the measurement program. Measurement of the clutter background is required to specify the test conditions, and in cases in which competitive sensor designs are evaluated, the same clutter background must be maintained for valid comparisons. In many cases the measured scattering response contains both far field and near field data; when target scattering data is derived, the range variations

should also be specified. In general, dynamic measurements of this type require more emphasis on calibration to obtain valid RCS data.

B. TARGET SUPPORT SYSTEMS

Static RCS measurements require a secure target support system that provides a low RCS return to avoid measurement inaccuracies. Dynamic measurements by their nature do not require specialized supports. The target support must position the target in the facility and provide an accurate, repeatable means of rotating the target so that different aspect angles can be measured. Generally, azimuth target rotations are used in RCS measurements. The target is repositioned on the azimuth mount to achieve coverage of the full spherical volume of the target.

A comprehensive discussion of the electrical and mechanical properties of various target support systems is given in Ref. 28. Very light targets can be supported and attached to the positioner with monofilament lines. More substantial targets can be supported by low density foam columns rotated by azimuth positioners. Shaping techniques can reduce the reflectivity of foam supports; techniques to estimate the RCS of these low density foam supports are described in Ref. 29. Large, heavy targets provide the biggest challenge for target support systems because the mechanical requirements for secure support strongly conflict with low reflectivity requirements. A clever solution for moderate weight targets and monostatic RCS measurements has been implemented with an inclined metal column specially shaped to provide a low backscatter to the radar. This column, illustrated in Fig. 5, presents an inclined wedge shape with a low RCS level to the radar and the rounded portions attenuate creeping wave returns that travel around the column. Analytic techniques to estimate the RCS return for such supports are described in Ref. 30. The column remains fixed and the target is rotated by a driveshaft within the column or by a motor enclosed within the target.

C. CALIBRATION STANDARDS

Both the relative RCS variation of the target and its absolute level must be determined. In principle, the absolute RCS level can be established by careful measurement of elements of the radar range equation described in

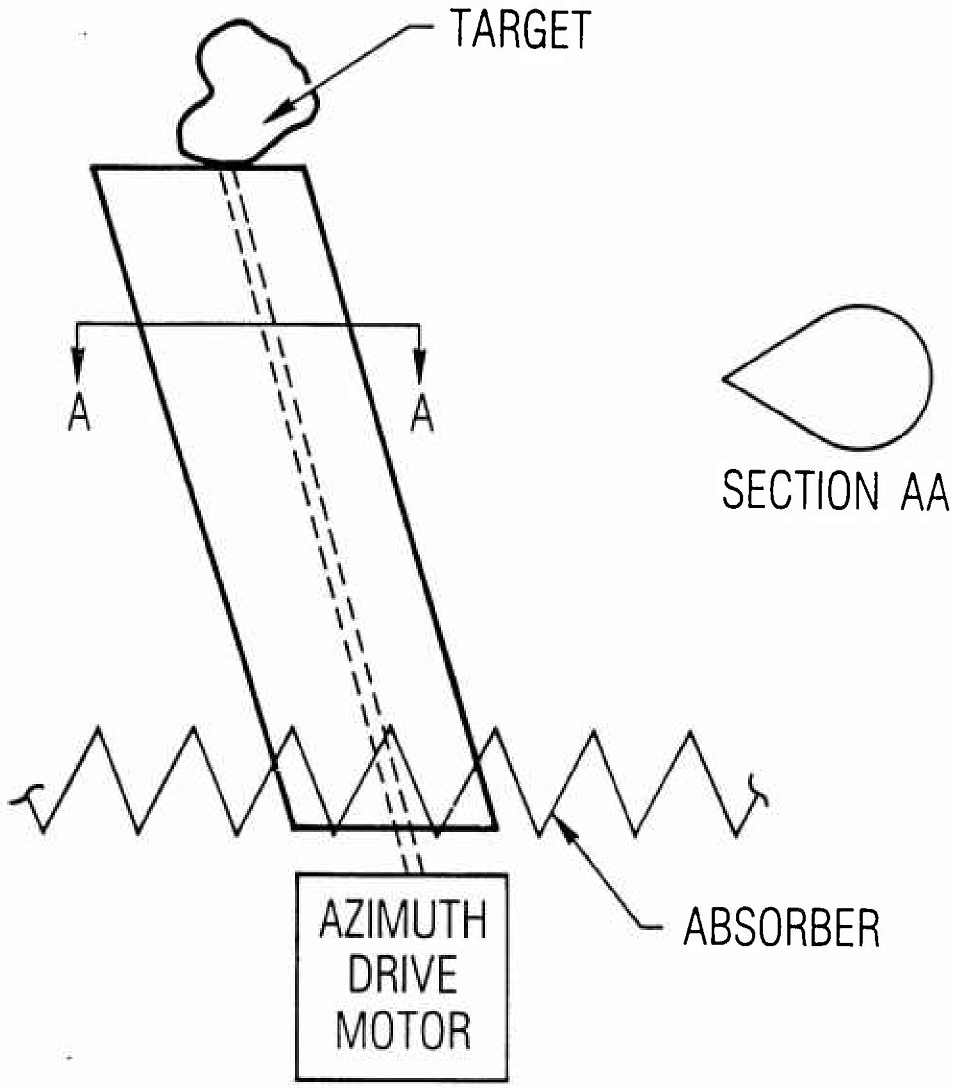


Figure 5. Metal Column Target Support Concept

Section IV. The overall accuracy in this calibration method is compromised by the accuracy with which the antenna gain, power levels, etc. can be measured. A more accurate method to establish the absolute RCS level uses a standard target that is substituted for the target being measured. This calibration technique is analogous to establishing of an antenna gain level by the substitution method. This method is widely used in static measurements and highly recommended for dynamic measurements if possible.

The most common calibration target is the conducting sphere for the following reasons:

1. Its RCS level is well established and can be calculated by well known techniques

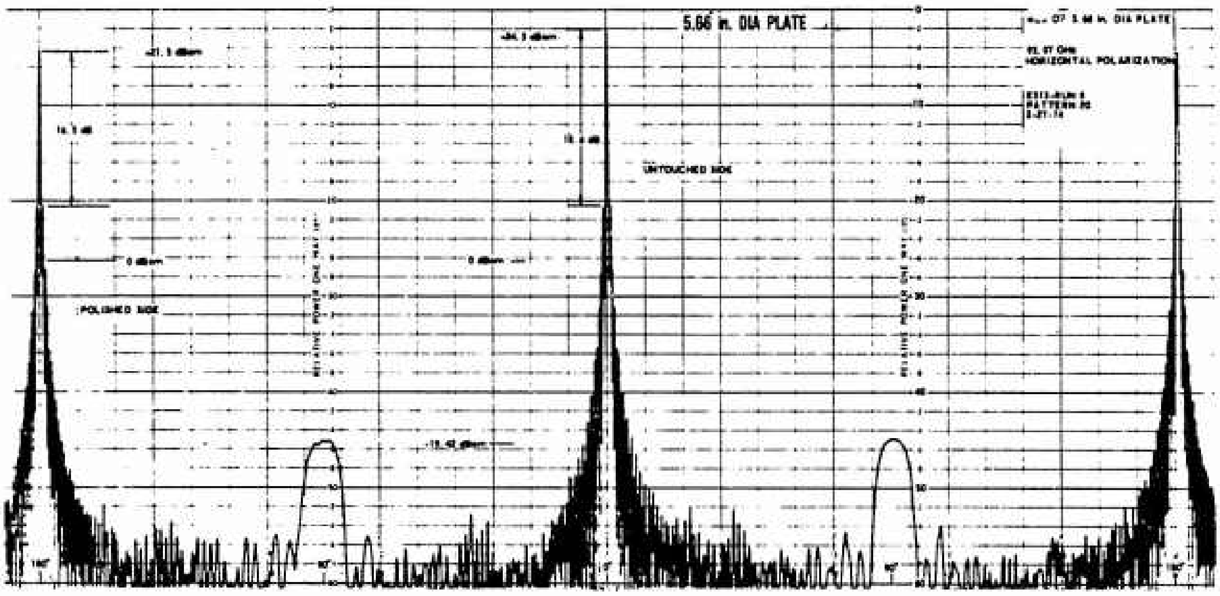
2. It does not require angular alignment

3. Its bistatic response is almost isotropic, except in the forward scattering region (180° bistatic angle), and provides sensitivity to multipath errors over a wide angular volume

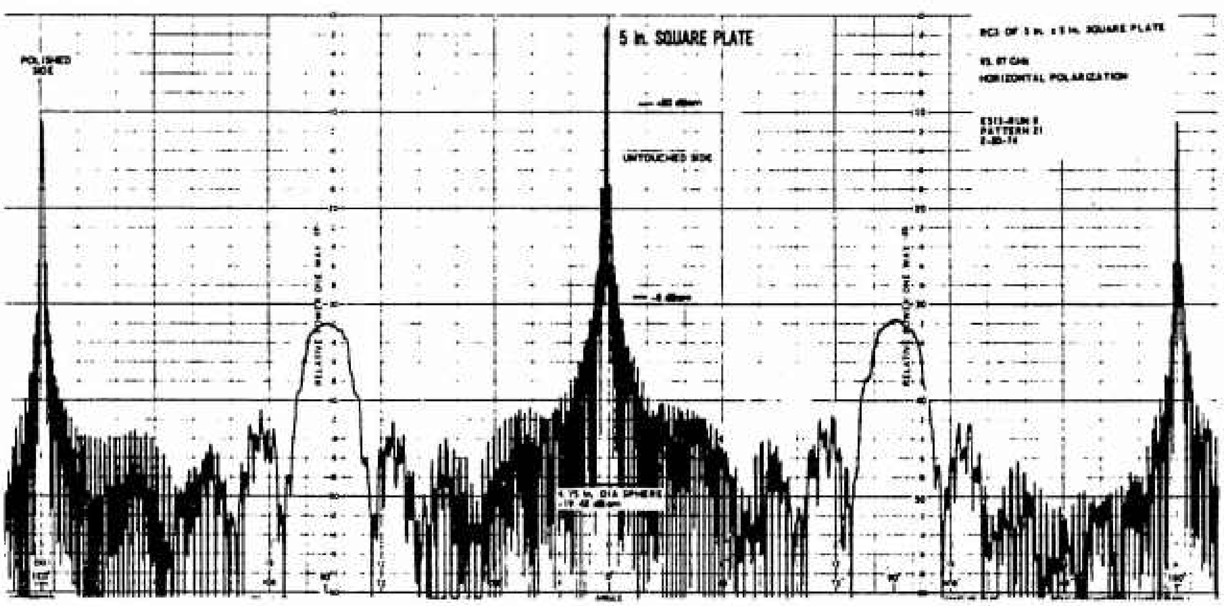
4. Its RCS level is relatively low, which increases the sensitivity to background RCS errors.

A particularly useful tabulation of the monostatic and bistatic RCS levels of spheres is given in Refs. 31 and 32, respectively.

Flat plate or corner reflector targets provide higher RCS levels than conducting spheres; a higher calibration target level is particularly desirable to separate the calibration from the background RCS level. Both targets must be aligned with the radar line of sight. With care, flat plate targets, as shown in Fig. 6, can be constructed with sufficient precision to yield almost a textbook response, even at 93 GHz (Ref. 33). The peak return of the flat plate, referred to as the "specular" response, is the orientation used for calibration purposes; i.e., the plate is aligned normal to the radar line of sight. The narrow width of this specular lobe illustrates the requirements for precision alignment. While the required alignment presents a burden, the positioning accuracy of the target support system is also evaluated. Corner reflectors have relatively high RCS returns over a wide angular region, which eases requirements for alignment in dynamic measurements. Both of these



(a) Circular Plate



(b) Square Plate

Figure 6. 93 GHz Measurements of Flat Plate RCS Calibration Targets

targets are restricted to monostatic systems; the RCS response of corner reflectors is particularly sensitive to the bistatic angle (Ref. 34).

Active coherent repeaters described in Fig. 7 provide a high level bistatic radar calibration target. Their RCS is given by

$$\sigma = (\lambda^2/4\pi)\, G_{rr}\, G_{tr}\, G \tag{2}$$

where G_{rr} and G_{tr} are the repeater antenna gain levels on receive and transmit, respectively, and G is the net electronics gain between the transmit and receive antennas. The effective field of view is controlled by the antenna beamwidths. The polarization properties are those of the transmit antenna; the polarization loss of the receiving antenna relative to the incident radar polarization is factored into the overall gain of the repeater that establishes the RCS level. The coherence time of the repeater depends on the short-term stability of the oscillator used for the frequency conversion, which is adequate for most applications. The radar bandwidth must be accommodated by the IF amplifier. The amplifier must be capable of a power output, P_{out}, equal to

$$P_{out} = \frac{P_t\, G_t\, \sigma}{4\pi R^2\, G_{tr}} \tag{3}$$

where P_t and G_t are the radar transmitted power and antenna gain, respectively, and R is the range separation. Sufficient isolation between the transmit and receive antennas must be maintained for stable operation. The thermal noise radiated by the repeater should be sufficiently low so that the system noise figure of the radar receiver is not degraded; the physical separation between the repeater and the radar receiver is effective in reducing this noise contribution. Examination of the link equation and the noise powers results in

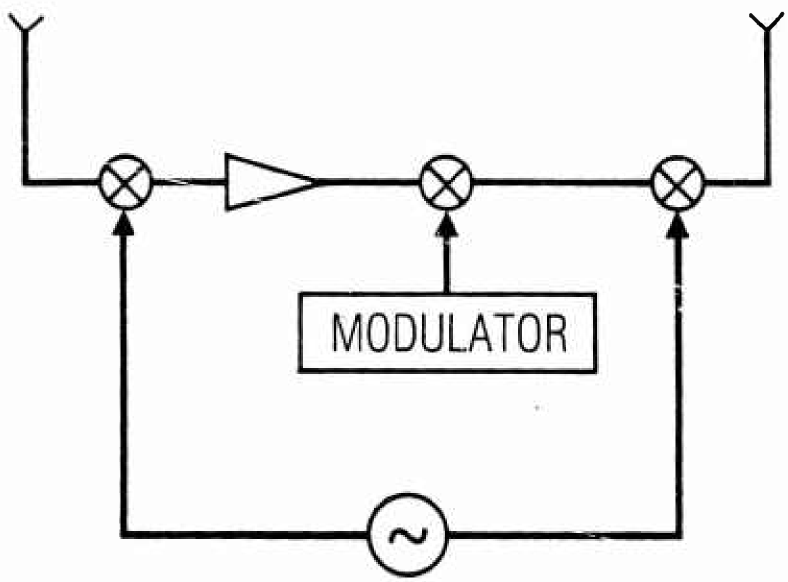


Figure 7. Functional Diagram of Repeater For Bistatic Radar Calibration

$$\frac{NF_r \ \sigma \ G_r}{4\pi \ R^2 \ G_{rr}} << NF \tag{4}$$

where NF_r is the noise figure of the repeater, G_r is the gain of the radar receiving antenna, and NF is the noise figure of the radar receiver. The inherent RCS return from the physical structure of the repeater must be controlled to reduce interaction with the return from the active repeater. This structural RCS return of the repeater can be determined from measurements taken with the active repeater turned off.

The repeater may be modulated to offset its return from the background clutter and the inherent structural return of the repeater. An X-band repeater system was used to calibrate a bistatic radar (Ref. 35); this system used 3 kHz single sideband modulation to create a synthetic doppler output for coherence periods up to 0.1 sec.

The comparison of several different calibration targets is highly recommended to add confidence in measurement accuracy. The relative differences between the measured levels for different calibration targets can be compared with the anticipated differences in their absolute levels. Spheres of different diameters, such as ball bearings of varying size, are a particularly expedient target collection. Analytic data are widely available for simple targets which can be used to increase measurement credibility. The correspondence between analytic data (Ref. 36) and VHF measurements of a dipole, shown in Fig. 8, is an example.

D. FACILITY EVALUATION

Facility evaluation is an important part of any measurement program, and the fundamental definition of RCS provides guidance for such evaluations. RCS facility evaluations address the success with which an incident plane wave is generated, the interaction between the target and the facility, and the facility background RCS which limits low level RCS accuracy.

The incident illumination provided by the facility can be directly measured. One technique is to move a probe antenna across the cross section of the facility and measure the amplitude and phase of the illumination field.

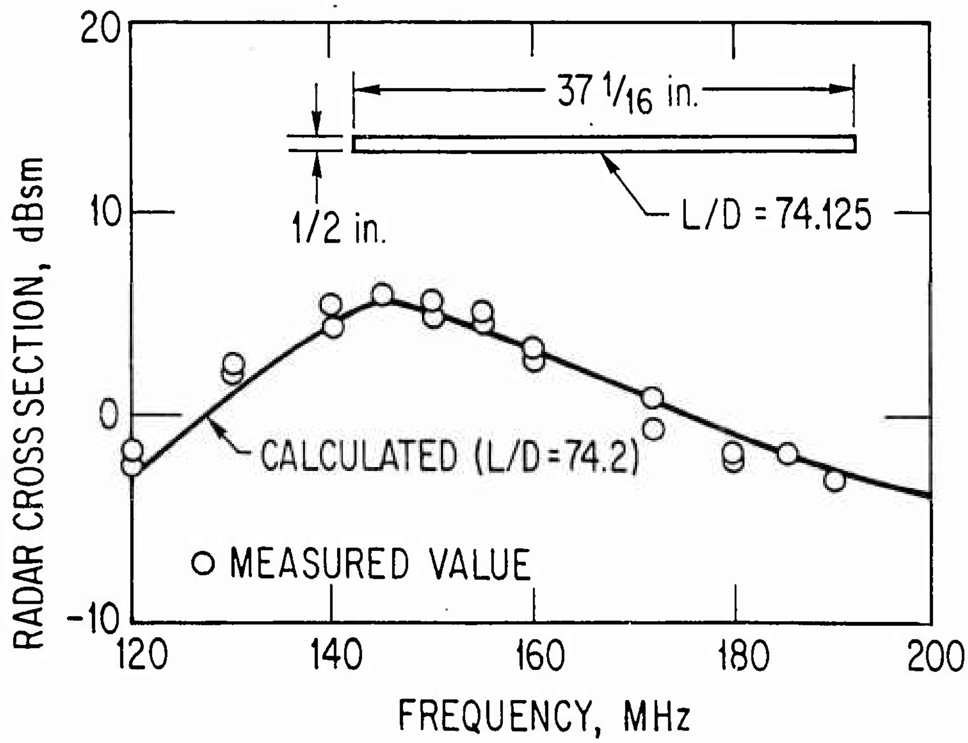


Figure 8. VHF RCS of Dipole (Calculated Data From Ref. 36)

These measurements are made in an antenna mode rather than a radar mode. The measurements can also be made by moving a small scatterer over the cross section of the facility and measuring the amplitude and phase of the response; the measurements in this form are made in a radar mode. The measurements over the cross section of the facility are repeated at different distances from the instrumentation radar. Such measurements characterize the field structure in a volume in which the target is to be located and measured; the volume over which the facility achieves the required closeness to plane wave illumination is commonly referred to as the "quiet zone."

The second task assesses potential interactions between the target and the surrounding facility. These measurements establish the level of multipath components which limit measurement accuracy. Typically, a small sphere is selected to provide a low level return that accentuates the multipath level and also provides an almost isotropic bistatic response to increase sensitivity to multipath distortion. The sphere is suspended in the facility and swung in both axial and transverse directions. Multipath components are indicated by the modulation which results from their interaction with the direct signal. The multipath source can sometimes be identified by observing the periodicity of the modulation and identifying a direction of arrival for that periodicity. The height of the sphere can also be varied to observe multipath components in a vertical direction. At high frequencies, the sphere must be moved sufficiently slowly so that the modulation is not doppler shifted beyond the receiver passband. The multipath level can be determined from the spread between maximum and minimum values of the modulation. The peak-to-peak ripple, discussed as a coherent error in Section V, Fig. 18, is used to derive the multipath level relative to that of the direct signal.

The third task in facility evaluation determines the background RCS level of the facility. Three components comprise this background RCS level. The first component is the background of the facility itself which is determined by measuring the empty facility and referencing its level to a calibration target. The second component is the target support system. The empty target support is measured in the facility and should be rotated to evaluate the support's azimuth variations. The third component is the residual isolation

between the instrumentation radar's receiver and transmitter. Isolation is a particular problem for CW instrumentation radars, and nulling circuitry is used to increase the isolation. The isolation of pulsed radars should be measured because of the large dynamic range between the transmitted power and received signal levels. The time gating in pulsed radars can isolate the individual components of the background RCS within the resolution capabilities of the waveform.

IV. INSTRUMENTATION RADARS

The instrumentation radar must have the capability to generate the radar waveform of interest, sufficient sensitivity to measure the target return with adequate accuracy at the required minimum RCS level, sufficient isolation between the transmitted waveform and the received, and ability to process and display measured data. The radar's antennas must have the required polarization capability, with sufficient purity to measure the desired polarization response of the target. The radar requirements will be reviewed and typical electronics will be described.

A. RADAR RANGE EQUATION

The radar range equation provides a basis to establish the radar sensitivity requirements. The radar range equation and its underlying assumptions illustrate the implicit dependence on far field conditions and the fundamental need to establish the RCS levels of targets for operational systems. The required isolation between the transmitted and received waveforms is determined from the radar range equation, and some of the factors that limit measurement accuracy are highlighted.

The radar range equation relates the ratio of the power available to the radar receiver, P_r, to the peak power output of the radar transmitter, P_t, as

$$P_r = \frac{P_t\ G_t}{4\pi R^2}\ \frac{\sigma}{4\pi R^2}\ \frac{\lambda^2}{4\pi}\ G_r\ L$$

$$= \frac{P_t\ G_t\ G_r\ (\sigma/\lambda^2)\ L}{(4\pi)^3\ (R/\lambda)^4} \qquad (5)$$

where

$G_{r,t}$ = the antenna gain on receive and transmit, respectively

σ = target RCS relative to the incident (transmit) and scattering (receive) polarization and radar orientation

λ = operating wavelength

R = range separation between the target and radar

L = system losses which include ohmic losses in radar components, propagation losses above free space, and processing losses.

The grouping of terms in the initial expression is, respectively: the power density incident on the target which is regarded as "plane" over the target extent; the transfer of incident illumination by the target RCS into an outgoing spherical wave; and the effective aperture area of the radar receiving antenna. This grouping of terms is illustrated in Fig. 9. The spatial orientation of the radar relative to the target is specified in a coordinate system embedded in the target. If a bistatic radar configuration is used, two range values are required: one is the transmitter-target separation for the incident power density, and the second is the target-receiver separation for the outgoing spherical wave component. For bistatic configurations, both the transmitter and receiver orientations must be specified in the coordinate system fixed to the target; i.e., the monostatic RCS is a function of two angular coordinates while the bistatic RCS is a function of four angular coordinates. The second expression in Eq. (5) normalizes the parameters, and σ/λ^2, which is commonly used in scaled measurements again appears. Dimensions specified in wavelengths are commonly used in electromagnetics. The sensitivity of the power transfer to range, $1/R^4$, should also be noted: significant increases in the range separation are accompanied by a drastic increase in the required radar resources.

The radar receiver must compete with three noise components: isolation, facility background RCS levels, and thermal receiver noise. Isolation and facility background RCS components are coherently related to the radar signal, while thermal noise is incoherent. The distinction between coherent and incoherent errors will be discussed in Section V. Isolation between the radar transmitter and receiver results from leakage between the electronics and antennas. Isolation is troublesome in CW radars, but is time-gated in pulsed systems. The facility background RCS component consists of contributions from the empty facility and the target support system, as previously discussed.

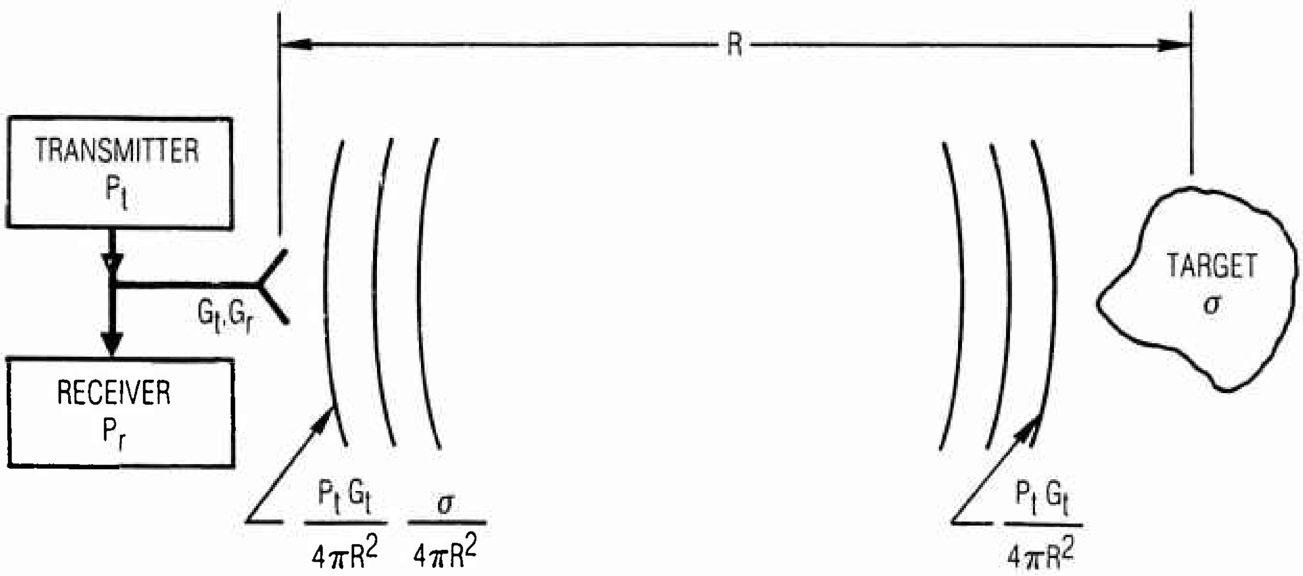


Figure 9. Link Geometry for Radar Measurements

The thermal noise component may be derived from the sensitivity specification of the instrumentation receiver, a measurement of the receiver noise power, or from the receiver noise figure and signal processing bandwidth. The receiver noise power can be conveniently measured by injecting signal power of a known level into the receiver and observing its level above the receiver noise. Estimates of the receiver noise power derived from the receiver noise figure and the signal processing bandwidth can be verified by a radar measurement of a calibration target. The estimate of the signal processing bandwidth is based on a "matched filter" bandwidth (Ref. 37). The difference between the measured signal-to-noise ratio and one projected from the radar component values and the matched filter projection of receiver noise power is the system loss component used in Eq. (4). A determination of the receiver noise power is fundamental to understanding the limitations of the radar sensitivity. In dynamic measurements the absolute RCS level is inferred from the measured signal-to-noise ratio, and the quantification of the receiver noise power is mandatory.

A graphical display of the various power levels given in Fig. 10 (Ref. 38) is particularly useful in establishing the radar requirements for anticipated measurements and in understanding the factors that limit accuracy. The minimum usable RCS level is established by the accuracy requirements for a specified RCS level, as shown in the figure. The achievable accuracy will be discussed in Section V. The dynamic range of the measurements extends from the maximum return level to the minimum usable level. The power levels indicated on the display illustrate the measurement limitations. If the facility background RCS level or radar isolation exceed the minimum usable RCS response, improvements must be made to the facility or to the isolation. The dynamic range of the measurements is limited by the coherent errors and no increase in transmitted power will improve the dynamic range. If the receiver noise level is the limiting factor, either a transmitter power increase or a receiver sensitivity improvement will expand the dynamic range of the measurements.

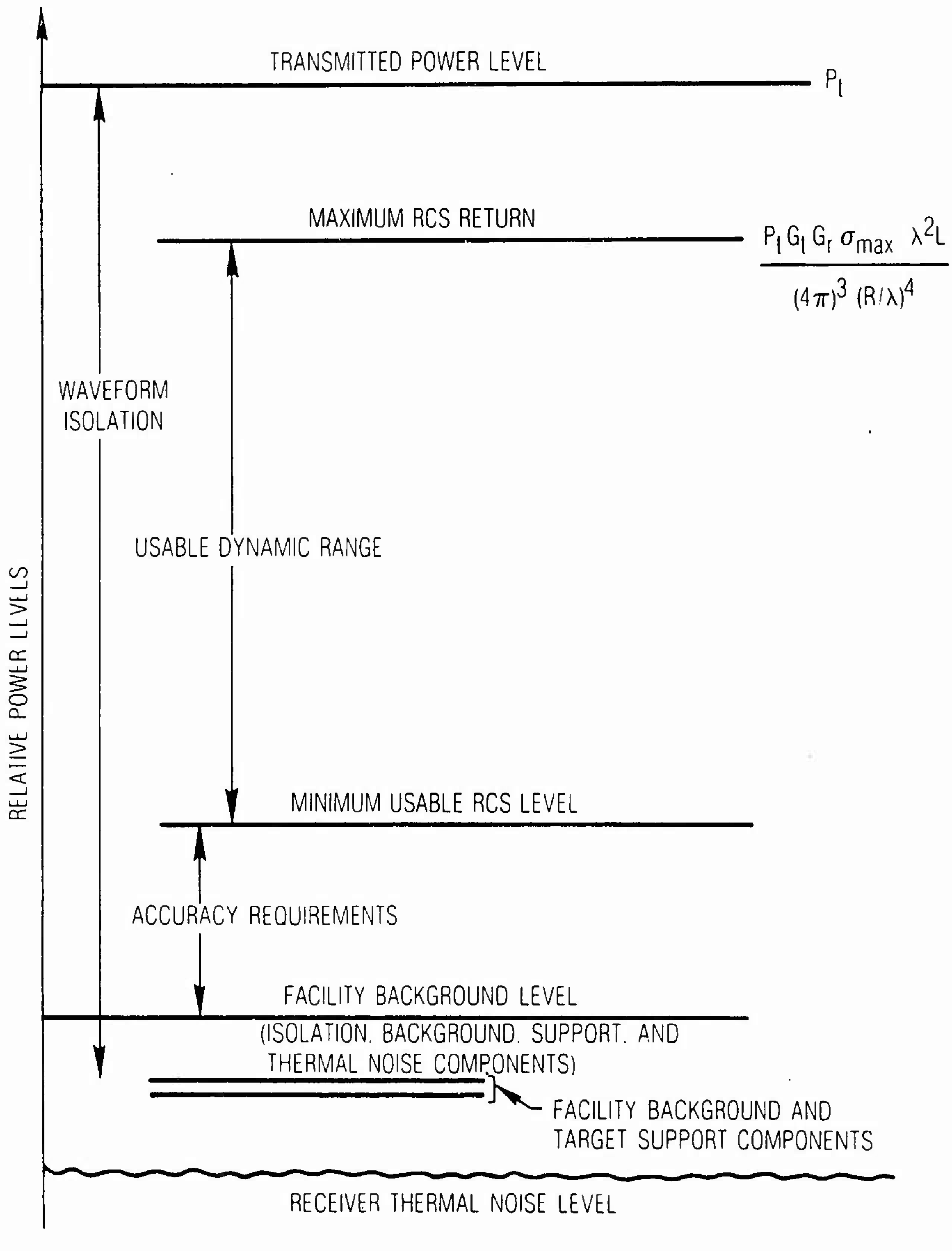


Figure 10. Relative Power Levels in RCS Measurements

B. INSTRUMENTATION RADARS

The instrumentation radar system may take various forms. Simple CW instrumentation radars configured from conventional microwave components and standard test receivers and transmitters have been widely used. The development of modern network analyzers has significantly enhanced these radars. While such systems can be readily constructed from general purpose electronics, the isolation between the receiver and transmitter limits their performance, and pulsed systems are required when the required isolation cannot be achieved. The present availability of broad bandwidth electronics and inexpensive signal processing technology, coupled with the desire to observe the details of the radar response, lead to high resolution instrumentation designs. Measurement programs that must determine the RCS response for a specified waveform and processing technique can be conducted with actual hardware or a specialized instrumentation radar constructed to replicate the operational system. As a practical matter, measurement program costs significantly increase with instrumentation radar complexity.

1. CW Radars

A typical CW instrumentation radar is illustrated in Fig. 11. The receiver and transmitter are connected to separate ports of a magic tee or hybrid, an antenna used for both transmitting the incident field and receiving the scattered field is connected to the third port, and nulling circuitry is connected to the fourth port. The nulling circuitry consists of amplitude and phase controls that adjust the impedance of the fourth port to maximize the isolation between the transmitter and receiver.

In operation the isolation is maximized without a target in the measurement facility by adjusting the amplitude and phase values in the nulling circuitry. This adjustment cancels both the isolation and background RCS components. The target is then inserted into the facility and measured without changing the nulling circuit adjustment. The target is then replaced by a calibration target to establish an absolute RCS level. Finally, the measurement of the empty facility is repeated to verify that the cancelled isolation level has not changed during the course of the measurements. Some

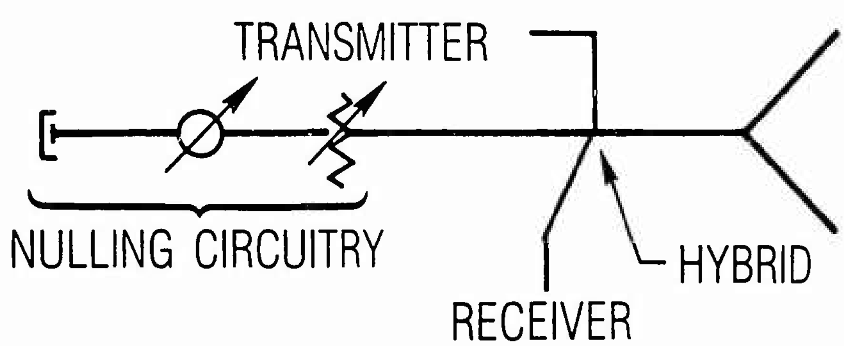


Figure 11. Block Diagram of CW Instrumentation Radar

variation in the cancelled level can be anticipated during the course of the measurements; an example of the variation during the course of VHF measurements ·· ·sented in Fig. 12. At the start of the measurements, the isolatio· was adjusted to at least an equivalent level of -45 dBsm (Ref. 15). Frequency accuracy and the stability of the measurement system are key requirements to maintain isolation for the period of time required by the measurements. The isolation performance that can be achieved in a typical instrumentation system is between 100 and 110 dB.

This isolation performance is limited by several factors. The impedances of the devices connected to the magic tee or hybrid ports must be well matched and stable in value. Other isolation paths, such as flange leakage, must be carefully controlled. The null achieved by the cancellation circuitry is very frequency sensitive (Ref. 39); the required transmitter stability is typically on the order of parts in 10^8, and phase lock circuitry is used to stabilize the transmitter. At low frequencies, the system null may be influenced by the presence of the operator and his interaction with the antenna. The nulling circuitry can be transferred to a remote location by a well supported phase stable cable, and the antenna is isolated in the measurement facility. At high frequencies the null response is limited by the phase stability of the impedances. In this case more isolation may be achieved by using separate transmit and receive antennas. At high frequencies a small physical separation between antennas is equivalent to a large number of wavelengths and significant isolation exists; the small physical separation also closely approximates monostatic conditions. The isolation may be enhanced when absorber-lined tunnels surround the antennas (Ref. 40). When separate antennas achieve adequate isolation, broad bandwidth measurements can be taken without adjusting of the nulling circuitry and without stringent frequency stability.

Modern network analyzers and frequency synthesizers have greatly expanded CW radar capabilities. Network analyzer measurements are considered as CW measurements because the CW RCS values are obtained at discrete frequencies over the measurement bandwidth. An early application of network analyzers to RCS measurements is described in Ref. 41. The received amplitude and phase

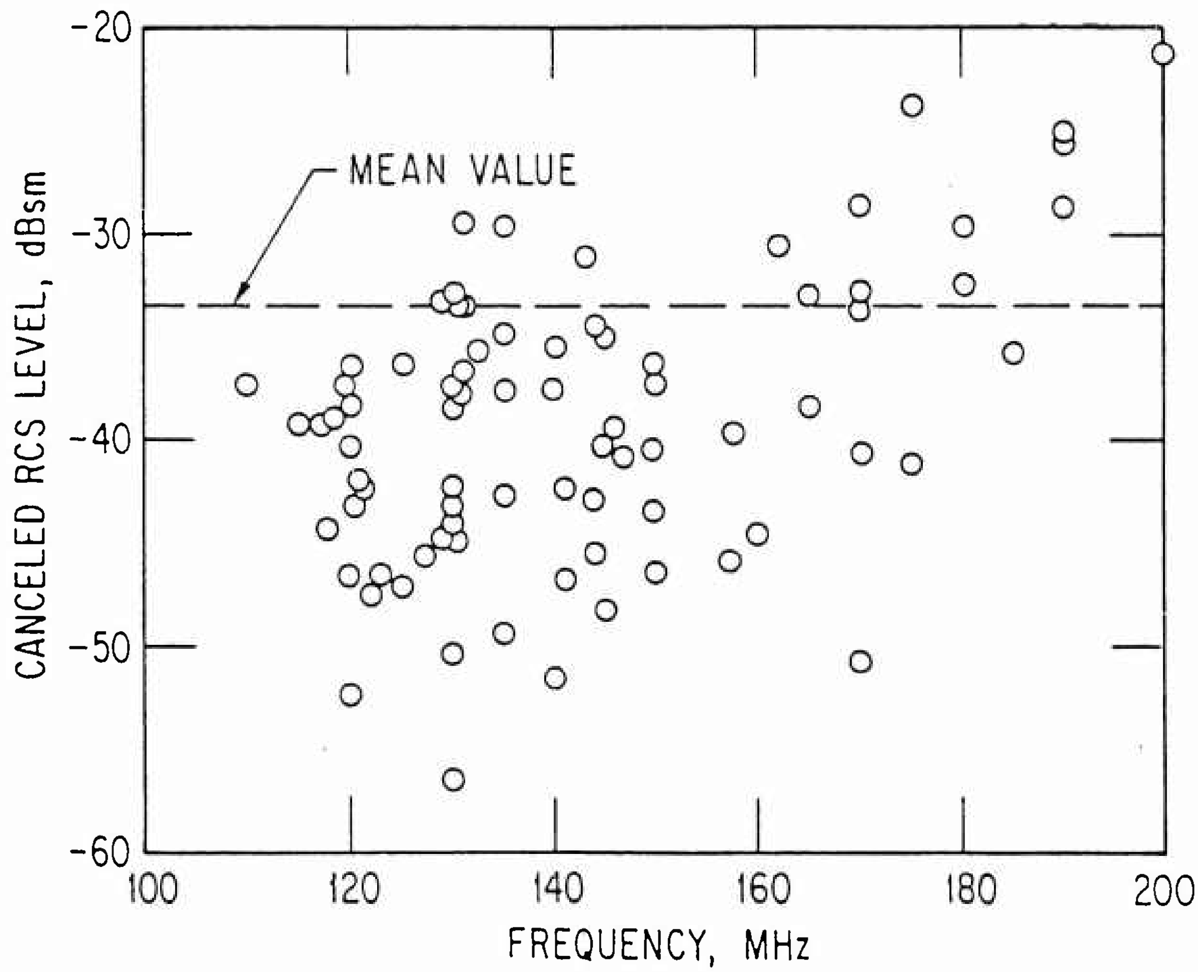


Figure 12. Variation in Background RCS at VHF after Measurement Interval

values, with and without the target in the facility, are measured as a function of frequency for different target orientations. The target return is then obtained from a vector subtraction of the target plus background and the background responses. The vector subtraction is equivalent to the nulling circuit adjustment at each frequency. An automated network analyzer was used to measure the RCS response of a target over an octave bandwidth. The dynamic range of these measurements is limited by the sampling accuracy and frequency stability and repeatability.

The transform techniques available in more modern network analyzer systems (Ref. 42) further increase measurement speed, convenience, and accuracy. The measured amplitude and phase values over a range of frequencies are transformed into the time domain where the target response and facility returns are displayed. The time domain response is windowed to isolate the target and transformed into the frequency domain. The windowing of the time domain response is analogous to pulsed radar operation. The spacing between frequency samples must be chosen to avoid aliasing. When sufficient bandwidth is used, the time domain response has the resolution necessary to observe RCS returns from different parts of the target. Experience with this technique is also described in Ref. 43.

A less costly time gating technique uses the recently developed broadband, low reflection switches with conventional instrumentation receivers and transmitters (Ref. 43). The timing between the switches is selected to isolate the target return. The instrumentation receiver operates in a conventional way to measure the RCS at a CW frequency, but the overall sensitivity is reduced by the square of the duty cycle. One duty cycle factor results from the reduction in average power, and the second duty cycle factor results because the receiver measures only the central lobe of the switched spectrum. In many applications the sensitivity loss is tolerable, and the target is isolated from the isolation and facility background components. This switching technique can also be applied to antenna measurements (Ref. 44).

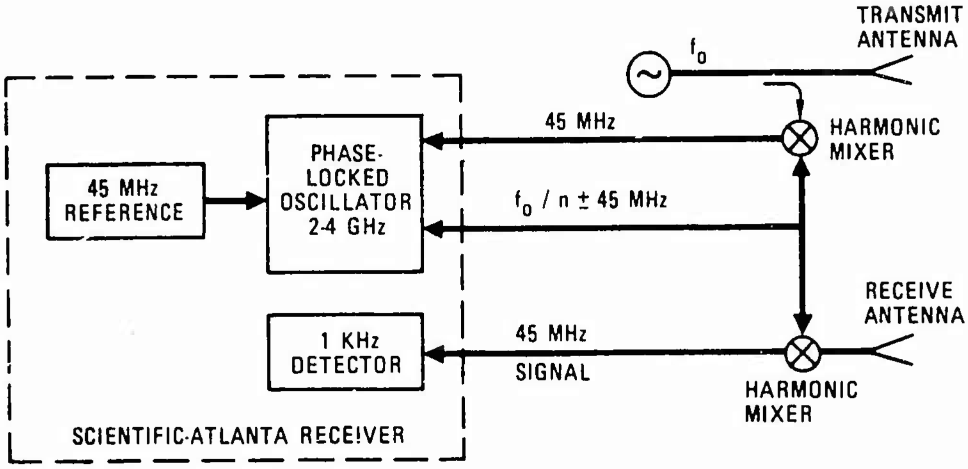
RCS measurements have expanded into millimeter wavelengths in recent years. The sensitivity of standard instrumentation receivers is reduced at

these frequencies because harmonic mixing techniques are used to extend the frequency coverage. The conversion loss of a harmonic mixer used in the receiver front end degrades with the square of the harmonic number. A large harmonic number is required at millimeter wave frequencies and a substantial sensitivity loss is incurred. A phase lock technique has been developed to use fundamental mixing in the receiver to recover the sensitivity loss (Ref. 45). Functional block diagrams of a conventional system and the phase locked system with improved sensitivity are presented in Fig. 13. A 30 dB sensitivity improvement was realized at Ka-band frequencies.

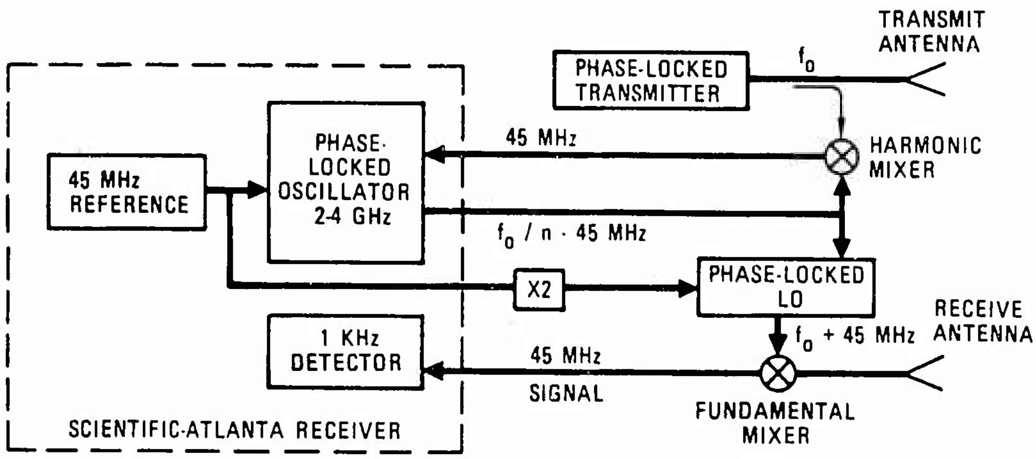
2. Pulsed Radars

Pulsed instrumentation radars are required when the achievable isolation limits the required minimum RCS level. Generally, the measurement of extremely large targets on ranges that exceed 1000 ft requires pulsed operation. The large range requirement results in practical pulse parameters and sufficient time to duplex (terminate the radar receiver during transmission periods) if required. Pulsed radars also reduce isolation components and portions of the background RCS that lie beyond the range interval containing the target.

A block diagram of a typical pulsed radar is shown in Fig. 14. The pulse duration for such systems is selected on the basis of several considerations. Component availability and performance is one factor. A pulsed system also unavoidably expands the bandwidth of the measurement, which must be considered if the measured target response is required to represent CW values. The bandwidth of an unmodulated pulse is to first order equal to the inverse of the pulse duration. The pulse duration must exceed the target dimensions by several multiples for a CW response. The range extent of the pulse and its rejection capability equal one-half the speed of light multiplied by the pulse duration. As an example, since the speed of light is approximately 1 ft/nanosecond, a 1 microsecond pulse covers a 500 ft range dimension. Specialized systems with very short duration transmitters are also used to identify individual features of the radar target. One example of short pulse system measurements is described in Ref. 46. These measurements cannot be considered narrowband.



(a) Conventional Operation



(b) Improved Sensitivity Operation

Figure 13. Millimeter Wavelength Instrumentation

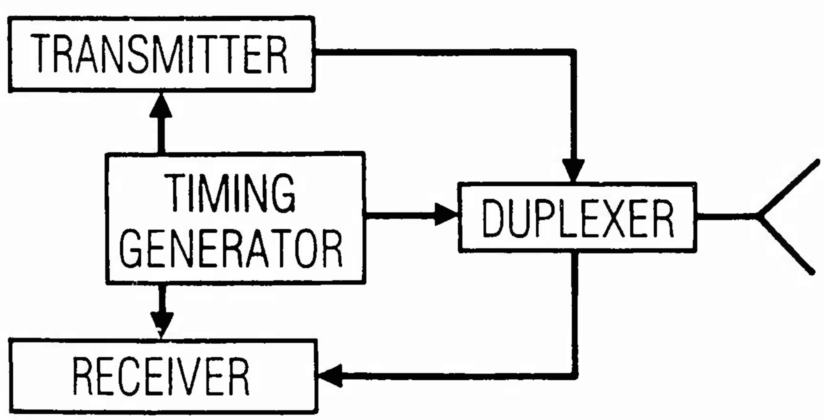


Figure 14. Pulsed Radar Block Diagram

3. High Resolution Radars

The availability of wide bandwidth electronics and frequency assignments (Ref. 47) that can support such bandwidths permits the development of high resolution radars. The general goal of operational high resolution systems is to enjoy the resolution performance of a short pulse system combined with the detection performance of a long pulse system. The tradeoffs associated with the waveform design have been described in Ref. 48 and further details of target imaging techniques are described in Ref. 49. High resolution instrumentation radars are required to assess operational radar performance and, with sufficient bandwidth, permit the measurement of radar returns from individual features of the target geometry.

The present popularity of dynamic measurements results from the desire to measure the detection performance of an operational radar waveform. Broadband electronics and frequency assignments provide many options besides high resolution processing. Frequency diversity, which hops a narrow bandwidth radar response over a broad bandwidth, is a simple way to use the broadband allocation without incurring significant processing complexity. Operationally, this technique offers the advantages of minimizing the probability of being in a null of the target response, reducing the phasing between target radar components which is the source of glint errors in tracking systems, decorrelating clutter effects, and diluting the effectiveness of electronic jamming. The evaluation of radar detection performance for diversity waveforms is a simple extension of CW measurement program requirements. While frequency diversity waveforms have broad bandwidths, these waveforms are not compressed to increase the range resolution, and are not considered as a high resolution waveform.

High resolution instrumentation radar requirements are more complex than those for CW or pulsed radars. High resolution radar responses are derived by transform processing the modulation added during the pulse duration. Independent of the precise modulation used for the waveform, the resolution achieved in range is given by

$$\delta_r = K\, c/(2B) \tag{6}$$

where K is a constant approximately equal to unity that depends on the weighting in the transform processing, c is the speed of light, and B is the bandwidth of the modulation used. Range resolution is defined as the range separation required to distinguish two equal targets. The bandwidth required to achieve this range resolution performance is presented in Fig. 15, which uses 1.3 as the value of K. When the bandwidth approaches 1 GHz, sufficient resolution exists to resolve the detailed structure of typical radar targets.

A wide bandwidth high resolution waveform does result in a penalty. The waveform processing compresses measurements for a finite bandwidth into a short pulse response by means of a transform technique. In common with any transform technique, finite responses exist beyond the region of interest; these responses are referred to as range sidelobes. The range sidelobe performance of a high resolution radar may be viewed as the radar system's response to an isolated point target as a function of range from the target. The range sidelobes from high level returns mask the low level returns. Unlike a true short pulse radar, the high resolution radar has a limited dynamic range over which target returns can be measured. Range sidelobe control, therefore, is another design issue for high resolution radar designs as it imposes amplitude and phase fidelity requirements over the waveform bandwidth. Amplitude weighting during the pulse interval is effective in reducing range sidelobe values at the expense of a minor loss in sensitivity and range resolution performance. The loss in range resolution performance is the reason that the value of K equal to 1.3 was used in Fig. 15.

Linear FM modulation, referred to as chirp, is the most popular way to increase the waveform bandwidth. The transmitted frequency varies in a linear fashion over the bandwidth required for range resolution during the pulse period. An example chirp instrumentation radar constructed easily from analog circuitry is described in Ref. 50, and a functional block diagram of this system is presented in Fig. 16. The transform processing used to obtain a high resolution response requires excellent waveform fidelity. This system uses leveling for amplitude control and a phase locked delay line discriminator for phase linearity. This system covered a 2 GHz bandwidth from 8.5 to 10.5 GHz. The amplitude weighting for range sidelobe control was $\cos^2 X$, and

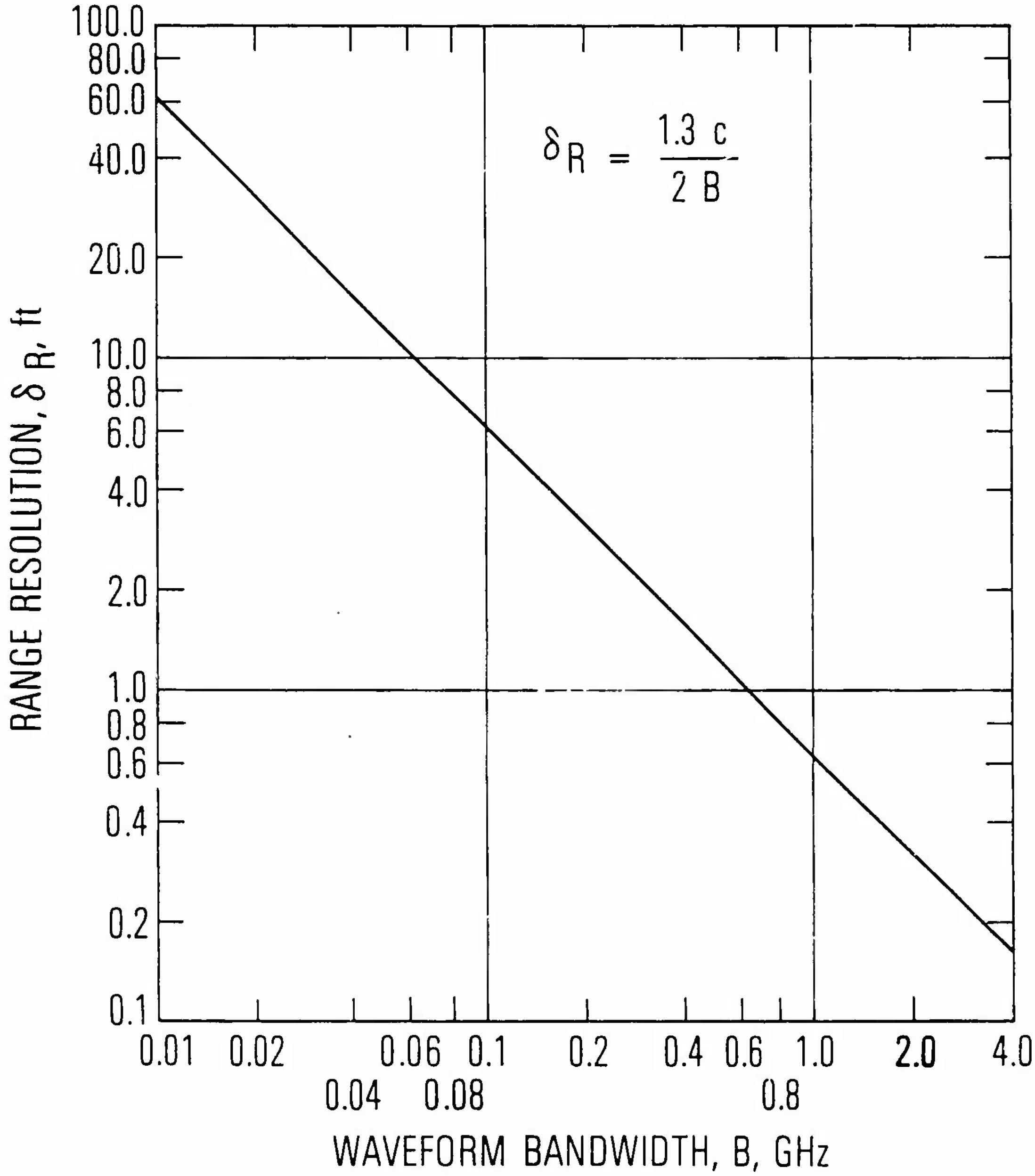


Figure 15. Radar Waveform Bandwidth Required to Achieve Range Resolution

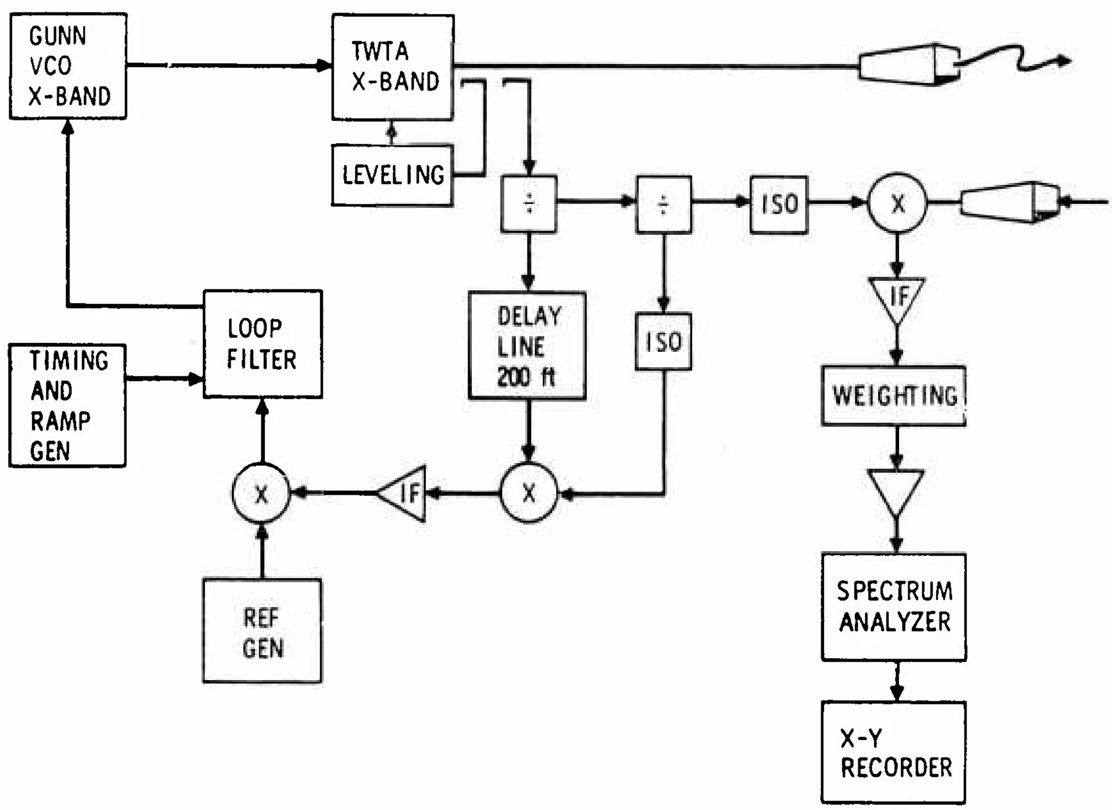


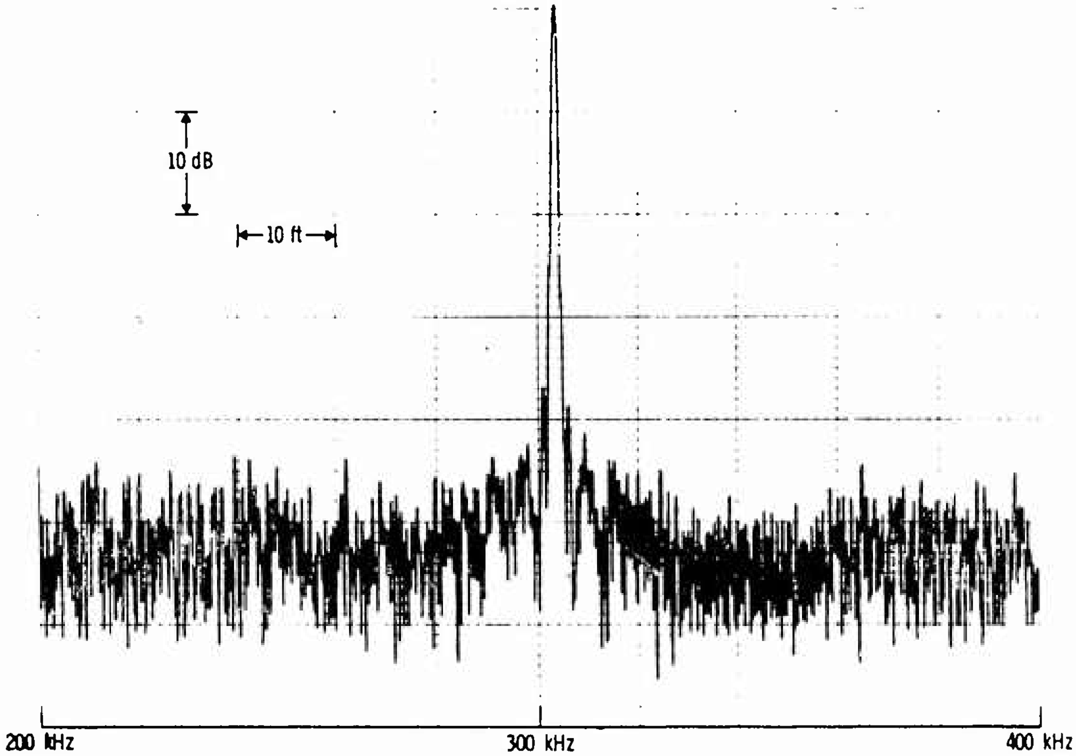
Figure 16. Functional Block Diagram of Chirp Instrumentation Radar

the measured range resolution, 4.9 in, closely agrees with the theoretical performance for this weighting. The measured range sidelobe performance for this radar, given in Fig. 17, indicates good waveform fidelity. Circuitry of this type has also been used at millimeter wavelengths (Ref. 51).

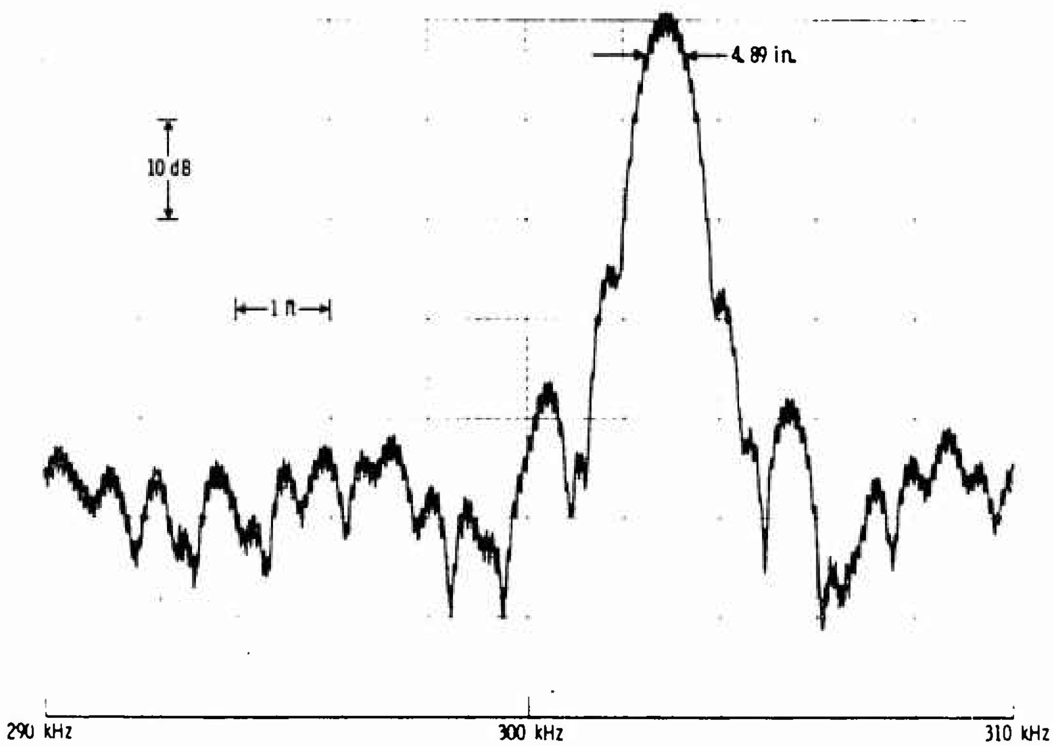
Another example chirp instrumentation radar (Ref. 52) has been used to generate both range and cross range radar responses. While the spectrum analyzer used in the former example provides a convenient, real time display, digital processing techniques increase the processing flexibility and can be supported with available technology. The range image is generated by the chirp waveform; the cross range image is generated by transform processing a series of range images taken with successive target rotations. The resolution in the cross range direction is given by

$$\delta_{cr} = \frac{k\lambda}{2\Delta\theta} \tag{7}$$

where λ is the operating wavelength, $\Delta\theta$ is the total angular rotation of the target, and k is again approximately unity depending on the amplitude weighting used in the transform processing. An example of a measured range and cross range image from Ref. 52 is given in Fig. 18 for a target drone vehicle.



(a) Performance over 100 ft Range Interval



(b) Expanded Scale $\pm$ 5 ft from Target

Figure 17. Measured Range Sidelobe Performance of Chirp Radar

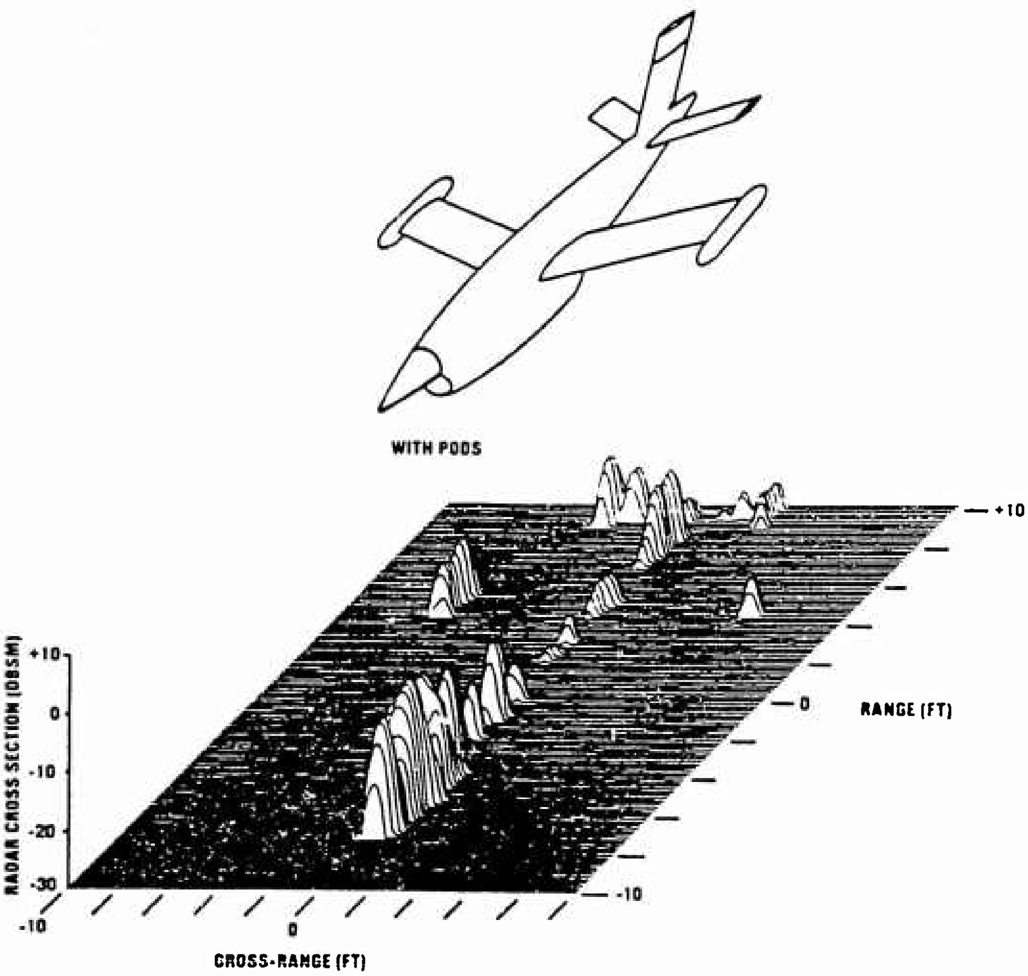


Figure 18. Range and Cross Range Image of Target Drone Vehicle (after Ref. 52)

V. MEASUREMENT ACCURACY

Accuracy is an important issue for any measurement program. For RCS measurements the accuracy of changes in the relative RCS level and the absolute RCS level is important. The absolute accuracy of RCS measurements depends on many factors, e.g., system stability, calibration standard accuracy, target and calibration standard positioning accuracy, facility error components, etc., as well as those factors that determine the relative accuracy. The relative accuracy depends on system linearity over the dynamic range of the measurements and on the errors induced by thermal noise and the coherent background RCS levels.

As a rule-of-thumb, absolute RCS accuracy under carefully controlled conditions is probably no better than 0.5 dB for static measurements and 2 dB for dynamic measurements. The larger errors for the dynamic case result from greater uncertainties in the radar parameters, range losses, calibration target level and alignment, receiver linearity, etc. Relative RCS accuracy is generally much better. The linearity of typical general purpose instrumentation, such as a network analyzer, is 0.1 dB/10 dB. At high RCS levels the relative accuracy principally depends on instrumentation linearity; in operation, measurements are referenced to the calibration standard RCS level and the system linearity errors are relative to that level. At low levels the relative accuracy degrades because of the interaction with background RCS components and thermal noise.

RCS measurement accuracy is generally projected by using an error budget to combine individual error components. In such error budgets, the random components are combined on an rss (root sum square) basis and added to the sum of the bias error components. Many of the error sources are specific to the measurement facility and instrumentation radar, and can be judged by repeated measurements to identify the particular components, which is sometimes a subjective process. A convenient ordering for purposes of discussion categorizes errors associated with the RCS definition, those associated with the measurement facility, and those associated with the instrumentation radar; this ordering follows the preceding discussion.

The errors associated with the RCS definition result from deviations in the plane wave illumination of the target and reception of the scattered spherical wave. Quadratic phase errors, for example, reduce the specular RCS levels somewhat, fill in the nulls of the RCS pattern surrounding the specular lobe, and vary the phasing between the component returns from the target. Such errors can be quantified on the basis of aperture integration with quadratic phase error (Ref. 53) for specular region returns (Ref. 9). Variations in the RCS lobe structure can be modeled by a collection of point sources having the same physical spacing and relative levels as the component returns for the aspect angle of interest. The lobe structure for this collection can be computed with and without quadratic phase error and the variation in the lobe structure can be observed from the differences in the computed results. The RCS definition implicitly assumes polarization properties for the incident illumination and scattered spherical waves. In practice, measurements are made with a finite cross polarization level. The polarization errors resulting from this finite cross polarization are discussed in Ref. 8.

The facility errors include the background RCS components and the calibration standard accuracy. The background RCS components previously discussed are coherently related to the radar waveform. The calibration standard accuracy involves both the accuracy with which its level is known and its positioning accuracy within the facility. Facility alignment errors can be determined by removing and replacing the calibration standard in the facility to obtain a repeated set of measurements. The set of repeated measurements should include variations of the incident and received polarizations to indicate multipath components; e.g., σ_{vv} measurements for a spherical target should equal σ_{hh} measurements. The calibration target location can be varied to determine potential multipath errors. The repeated measurements also provide an opportunity to observe the long term stability of the radar system.

The background RCS components include contributions from the facility itself, from the target support system, and from the isolation between the instrumentation radar receiver and transmitter. Each of these components should be individually examined and combined in the error budget. The individual levels may be used directly in the error budget for CW measurements;

for broadband measurements each component error must be weighted by the autocorrelation function of the waveform, with the time delay of each error component referenced to the target location.

The instrumentation radar errors include linearity over a dynamic range and thermal noise errors at the minimum RCS levels. In dynamic measurements, pointing errors and range tracking errors must be also included. Validation of manufacturer's data on these error values is recommended.

The first and second order component error statistics are required to apply the error budget to a particular measurement application. The first order, or mean, errors are summed to obtain the bias error. The second order, or standard deviation, or rms, errors are summed in an rss manner. The individual error sources can be further separated into coherent and incoherent errors. Coherent errors, e.g., background RCS errors, are related to the radar waveform. Incoherent errors, e.g., thermal noise, have no relation to the radar waveform. The errors are referenced to a specified RCS level; the minimum usable RCS level in Fig. 10 is used for this purpose.

Incoherent error statistics typically assume Gaussian statistics. The statistics were originally applied to radar applications by Woodward (Ref. 54). Further discussions of these statistics (Ref. 55) and their applications to radar measurements (Ref. 56) extend the original work. Gaussian error analyses typically assume zero mean error. The rms power errors are inversely proportional to the square root of twice the signal to noise ratio; power errors are cited because RCS is a power relation. Typical rms error values are shown in Fig. 19.

The first and second order statistics for coherent errors have been recently derived (Ref. 57). Statistics for power errors apply to RCS values because RCS is defined as a power relation. Statistics for amplitude and phase have application as well; e.g., the scattering matrix transformation for polarization uses amplitude and phase quantities. The derivation of the statistics proceeds by assuming that the true value has a unit amplitude and the error component has a relative amplitude a and a phase with respect to the true value. The phase, α, is assumed equally likely and uniformly

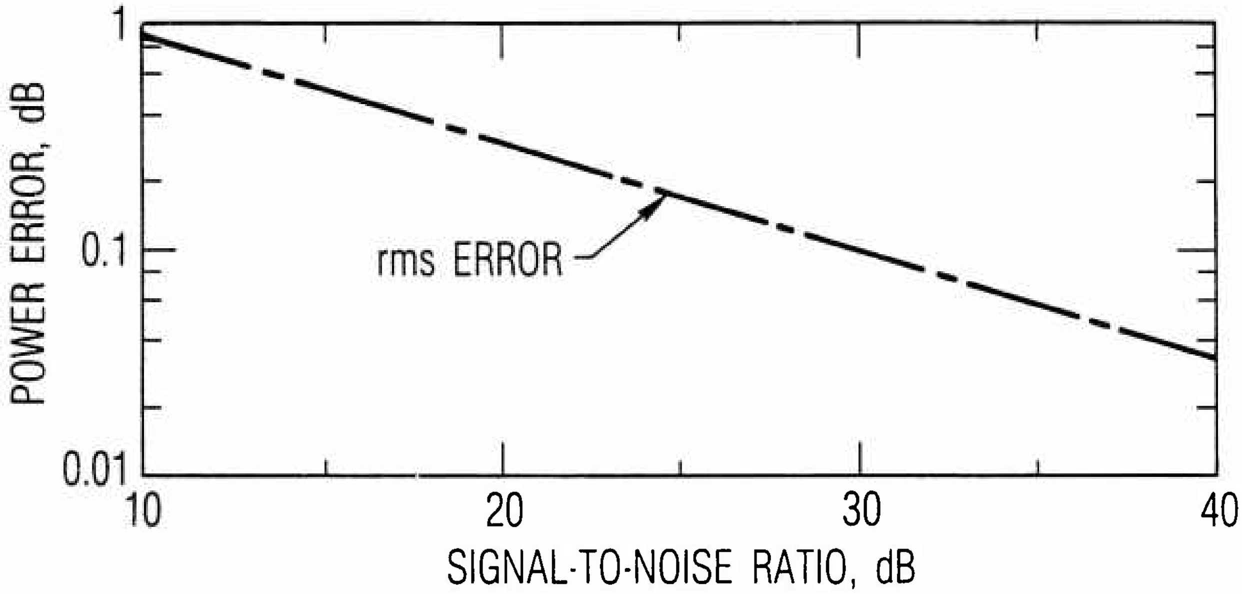


Figure 19. Incoherent rms Error Statistics

distributed from 0 to 2π. These assumptions correspond to a physical error model in which the error component is related to the desired signal, the relative amplitude is constant, and its phase is indeterminate. The differences in statistical assumptions between incoherent and coherent errors are worth contrasting. Incoherent error statistics assume that a sufficiently large number of statistically similar error components exist to apply the Central Limit Theorem to justify Gaussian statistics. The coherent error statistics assume that an individual error component is related to the true value with unknown phasing.

The resultant power is the phasor sum of the true value and the error component, which is given by

$$P_{rec} = 1 + a^2 + 2\,a\,\cos\,\alpha \tag{8}$$

Since the true value is unity, the error is obtained by subtracting 1 from this expression. The voltage is given by the square root of Eq. (6). The peak-to-peak errors are obtained by setting α to 0 and π, are commonly used. The mean and rms power errors may be easily obtained by direct integration. The mean power error equals a^2, in contrast to the incoherent case, which has a zero mean error. The rms power error is similarly obtained by direct integration and equals $\sqrt{2}\,a$. The statistics for the voltage errors can be derived in closed form and expressed in terms of a complete elliptic integral of the second kind. Series expansions with good accuracy for $a < 0.5$ (-6 dB) were obtained for the statistics. The mean voltage error is approximately equal to $a^2/4$, and the rms error is approximately equal to $a/\sqrt{2}$.

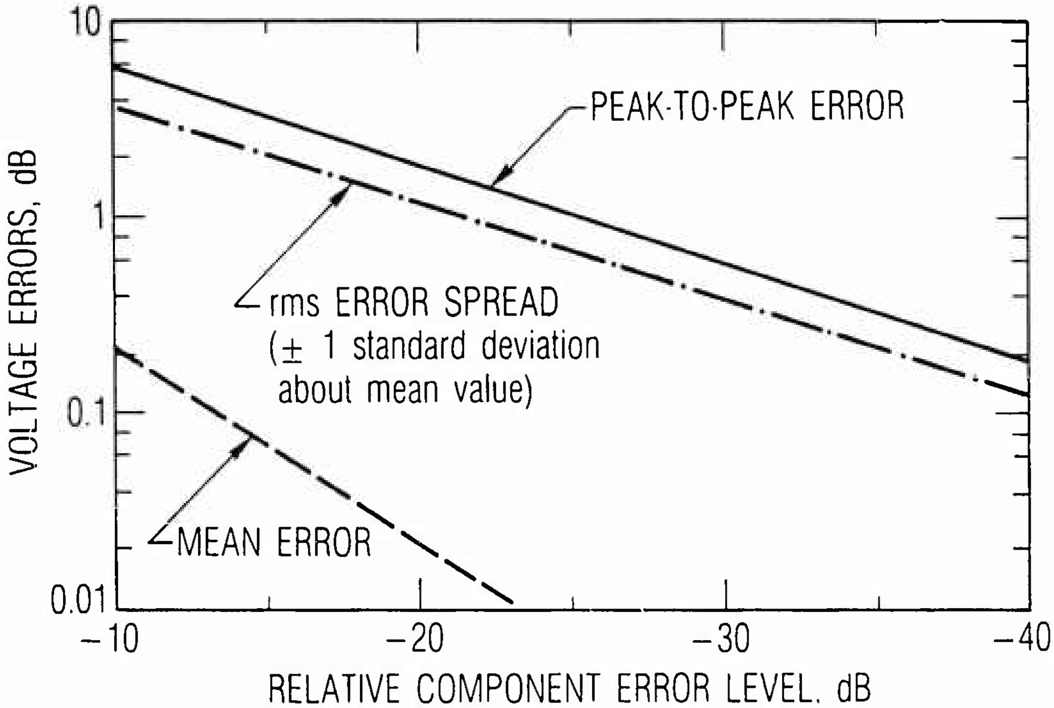
The coherent phase error statistics can be obtained from a similar process. The phase error is given by

$$\varepsilon = \tan^{-1}\left((a\,\sin\alpha)/(1 + a\,\cos\alpha)\right) \tag{9}$$

The mean phase error can be demonstrated to equal zero. The standard deviation of the phase error is difficult to derive in closed form. An approximate

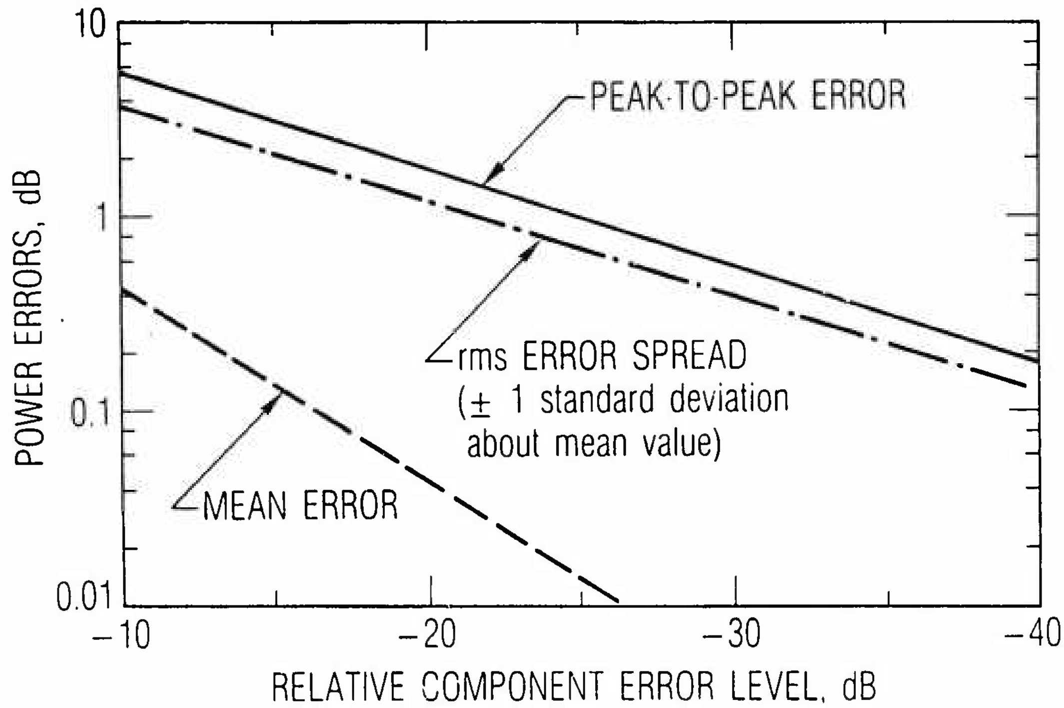
rms phase error value is $a\sqrt{2}$, which has been found accurate for $a > 0.5$ (-6 dB). The derivation of the statistical values is described in Ref. 48.

Example values of the coherent error statistics are given in Figure 20, for power, voltage, and phase errors. The peak-to-peak errors are commonly known. Since power and voltage are commonly expressed as dB variations, the rms errors are expressed as a $\pm 1\sigma$ spread about the mean error value. In comparison with incoherent error statistics, the coherent power and voltage errors have nonzero mean values, and the standard deviation of all three quantities is larger than their corresponding incoherent error values.

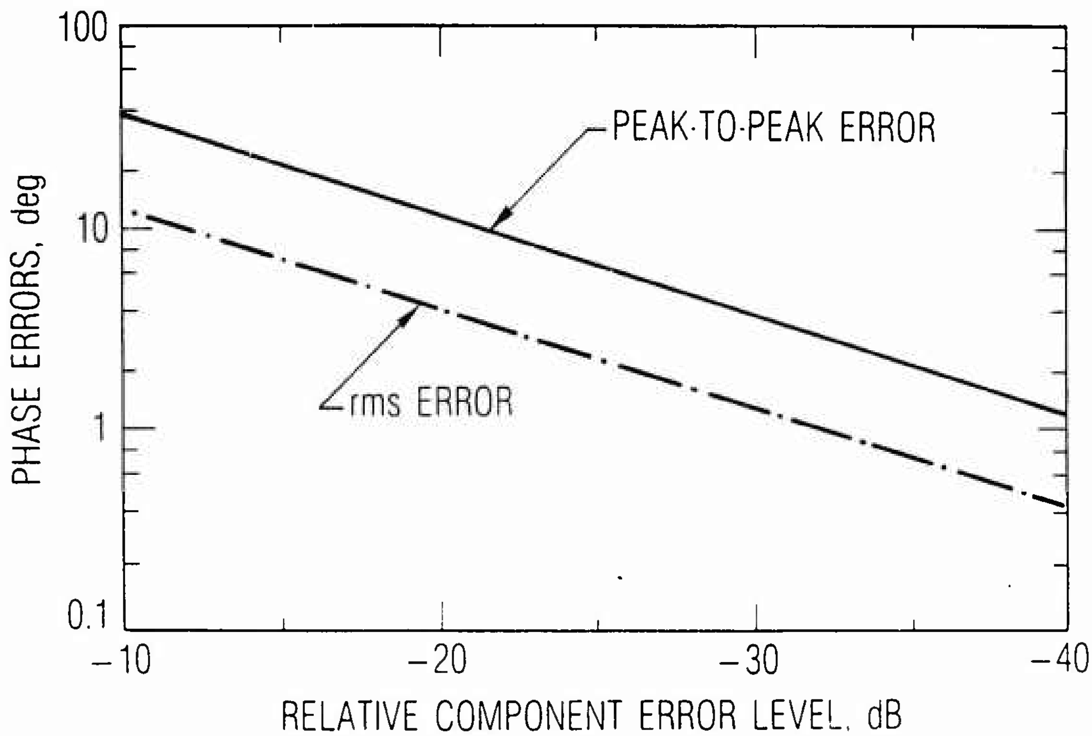


(a) Power Errors

Figure 20. Coherent Mean and rms Error Statistics



(b) Voltage Errors



(c) Phase Errors

Figure 20. Coherent Mean and rms Error Statistics (Continued)

VI. SUMMARY

RCS measurement techniques have developed over the last forty or so years and are well established. Recent progress in measurement techniques has been encouraged by the present growth in radar systems and, as with radar technology, has benefited from broad bandwidth electronics, signal processing techniques, and digital computer techniques. The earlier objectives of determining radar detection performance and understanding the radar scattering process have expanded to emphasize and support radar processing techniques. The recent active development of compact range designs and the use of transform techniques in measurement processing are evidence that the progress in RCS measurement techniques is accelerating.

These surveys tempt their authors to project the future. While such "crystal ball" projections have their obvious limitations, several trends are evident. A more general understanding of target properties will be required to distinguish different types of targets and separate targets from a clutter background. Such studies can be expected to emphasize target responses to waveforms having broad bandwidths and to explore further the polarization characteristics of targets. Further determination of the millimeter wave target response can also be anticipated from the availability of wide frequency allocations, increased resolution performance, and the availability of component technology that supports both experimental and operational systems. Advances in signal processing techniques and digital technology will also have a significant impact on the development of both measurement and operational systems. While a rich heritage already exists, future expansion for RCS measurement techniques can be readily foreseen.

REFERENCES

1. G. Sinclair, "Early History of the OSU ElectroScience Laboratory," IEEE Trans. Antennas and Propagation, AP-33, pp. 137-143, February 1985.

2. W. H. Kummer and E. S. Gillespie, "Antenna Measurements," Proc. IEEE, 66, pp.483-507, April 1978.

3. ..., IEEE Standard Test Procedures for Antennas, IEEE Std. 149-1979, Wiley-Interscience, 1979.

4. P. Blacksmith, Jr., R. E. Hiatt and R. B. Mack, "Introduction to Radar Cross-Section Measurements," Proc. IEEE, 53, pp.901-920, August 1965.

5. G. T. Ruck, D. E. Barrick, W. D. Stuart, and C. R. Krichbaum, Radar Cross Section Handbook, Plenum Press, 1970.

6. ..., Workshop on Polarimetric Radar Technology, sponsored by U.S. Army Missile Command, digests issued by GICIAC, ITT Research Institute, Chicago, IL.

7. E. M. Kennaugh, "Research Studies on the Polarization Properties of Radar Targets," Commemorative Volume I and II, ElectroScience Laboratory, July 1984.

8. R. B. Dybdal, "Cross Polarization Errors in RF Measurements,' Proceedings Second Workshop on Polarimetric Radar Technology, GICIAC, ITT Research Institute, Huntsville, AL, 3-5 May 1983.

9. R. G. Kouyoumgian and L. Peters, Jr., "Range Requirements in Radar Cross Section Measurements," Proc. IEEE, 53, pp. 920-928, August 1965.

10. J. A. Stratton, Electromagnetic Theory, McGraw Hill, 1941, pp. 488-490.

11. M. J. Gans, "The Transmission Line Scattering Range," Proc. IEEE 53, pp. 1081-1082, August 1965.

12. P. Beckmann and A. Spizzichino, The Scattering of Electromagnetic Waves from Rough Surfaces, Pergamon Press, 1963.

13. H. C. Marlow, D. C. Watson, C. H. Van Hoozer, and C. C. Freeny, "The RAT SCAT Cross-Section Facility," Proc. IEEE, 53, pp. 946-954, August 1965.

14. W. H. Emerson, "Electromagnetic Wave Absorbers and Anechoic Chambers Through the Years," IEEE Trans. Antennas and Propagation, AP-21, pp. 484-490, July 1973.

15. R. B. Dybdal and C. O. Yowell, "VHF to EHF Performance of a 90-ft Quasi-Tapered Anechoic Chamber," IEEE Trans. Antennas and Propagation, AP-21, pp. 579-581, July 1973.

16. J. R. Mentzer, "The Use of Dielectric Lenses in Reflection Measurements," Proc. IRE, 41, pp. 252-256, February 1953.

17. R. C. Johnson, H. A. Ecker, and R. A. Moore, "Compact Range Techniques and Measurements," IEEE Trans. Antennas and Propagation, AP-17, pp. 568-576, September 1969.

18. T. S. Chu and R. H. Turrin, "Depolarization Properties of Offset Reflector Antennas, IEEE Trans. Antennas and Propagation, AP-21, pp. 339-345, May 1973.

19. A. G. Repjar and D. P. Kremer, "Accurate Evaluation of a Millimeter Wave Compact Range Using Planar Near-Field Scanning," IEEE Trans. Antennas and Propagation, AP-30, pp. 419-425, May 1982.

20. D. W. Hess, F. G. Willwerth, and R. C. Johnson, "Compact Range Improvements and Performance at 30 GHz," 1977 IEEE Antennas and Propagation Symposium Digest, pp. 264-267, Stanford, CA, 20-22 June 1977.

21. W. D. Burnside, M. C. McGilreath, B. M. Kent, and G. C. Clerici, "Curved Edge Modification of Compact Range Reflector," 1985 IEEE Antennas and Propagation Symposium Digest, pp. 673-676, Vancouver, Canada, 17-21 June 1985.

22. D. J. Heedy and W. D. Burnside, "An Aperture-Matched Compact Range Feed Horn Design," 1985 IEEE Antennas and Propagation Symposium Digest, pp. 571-574, Vancouver, Canada, 17-21 June 1985.

23. V. J. Vokurka, "Compact-Antenna Range Performance at 70 GHz," 1980 IEEE Antennas and Propagation Symposium Digest, pp. 260-263, Quebec, Canada, 2-6 June 1980.

24. F. Pasqualucci, J. A. Paul, J. H. Andrews, J. K. Conn, and L. S. Gans, "The Compact Range RCS Measurement System," 1985 Antenna Measurement Techniques Association Symposium Digest, pp. 12-1 - 12-13, Melbourne, FL, 29-31 October 1985.

25. R. C. Rudduck, M. C. Liang, W. D. Burnside, and J. S. Yu, "Feasibility of Compact Ranges for near Zone Measurements," 1985 IEEE Antennas and Propagation Symposium Digest, pp. 669-671, Vancouver, Canada, 17-21 June 1985.

26. L. Peters, Jr., and F. C. Weimer, "Tracking Radars for Complex Targets" Proc. IEEE, 110, pp. 2149-2162, December 1963.

27. D. E. Kerr, Propagation of Short Radio Waves, McGraw-Hill, 1951, Chap. 6.

28. C. C. Freeny, "Target Support Parameters Associated with Radar Reflectivity measurements," Proc. IEEE, 53, pp. 929-936, August 1965.

29. M. A. Plonus, "Scattering from Low-Density Dielectric Bodies," IEEE Trans. Antennas and Propagation, AP-15, pp. 437-441, May 1967.

30. R. C. Rudduck, S. H. Lee, and T. Jorapunth, "Radar Cross Section for Standard Cylinder Targets and Target Support," ElectroScience Lab Tech. Rept. 784698-1, October 1978.

31. J. Rheinstein, "Tables of the Amplitude and Phase of the Backscatter from a Conducting Sphere," Lincoln Lab Group Report 22G-16, June 1963.

32. R. A. Ross and C. N. Cohen, "Circular Polarization Scattering Coefficients for the Bistatic Scattering of Electromagnetic Waves from Perfectly Conducting Spheres," Lincoln Lab. Tech. Note 1976-34, 27 July 1976.

33. R. B. Dybdal and H. E. King, "93-GHz Radar Cross Section Measurements of Satellites Elemental Scatterers," Aerospace Corp. Tech. Rept. TR 0075(5230-40)-4, 10 April 1975; selected data also published in R. B. Dybdal and H. E. King, "93-GHz Radar Cross Section Measurements of Satellite Elemental Scatterers," IEEE Trans. Antennas and Propagation, AP-25, pp. 579-581, May 1977.

34. L. Peters, Jr., "Passive Bistatic Radar Enhancement Devices," Proc. IEEE, 109, Part C, 15, pp. 1-10, March 1962.

35. C. J. Carter, R. B. Dybdal, H. E. King, R. J. Lioio, T. T. Mori, H. Nakamura, and J. S. Avrin, "Bistatic Radar Experiment with a Spaceborne Transmitter," Aerospace Corporation Tech. Report ATR 78(8215)-1, 29 September 1978.

36. R. F. Harrington, Field Computation by Moment Methods, MacMillan, 1968, p. 77.

37. G. L. Turin, "An Introduction to Matched Filters," IRE Trans. Information Theory, IT-6, pp. 311-329, July 1960.

38. J. N. Hines and T. E. Tice, "On Investigation of Reflection Measuring Equipment," Ohio State Antenna Lab Tech. Report, 478-13, June 1953.

39. R. G. Kouyoumjian, "The Calculation of the Echo Area of Perfectly Conducting Object by the Variational Method," Ohio State PhD Dissertation, 1953.

40. C. O. Yowell and R. D. Etcheverry, "Millimeter Wave Isolation Measurements of Diagnoal Horns and Tunnel Antennas," 1974 International IEEE/AP-S Symposium, Atlanta, GA, 10-12 June 1974, pp. 57-59.

41. W. B. Weir, L. A. Robinson, and D. Parker, "Broadband Automated Radar Cross Section Measurements," IEEE Trans. Antennas and Propagation, AP-22, pp. 780-784, November 1974.

42. ..., "Radar Cross-Section Measurements with the HP 8510 Network Analyzer," Hewlett-Packard Tech. Note 8510-2, April 1985.

43. E. K. Walton and J. D. Young, "The Ohio State University Compact Radar Cross-Section Measurement Range," IEEE Trans. Antennas and Propagation, AP-32, pp. 1218-1223, November 1984.

44. W. D. Burnside and M. C. Gilreath, "Pulsed Transmission Used for Improved Antenna Pattern Measurements," 1985 Antenna Measurement Techniques Association Symposium Digest, pp. 42-1 - 42-22, Melbourne, FL, 29-31 October 1985.

45. R. B. Dybdal, T. T. Mori, and H. E. King, "High Sensitivity Millimeter-Wave Instrumentation," 1981 IEE Antennas and Propagation Symposium Digest, Los Angeles, CA, pp. 119-122, 16-19 June 1981; see also, T. T. Mori, R. B. Dybdal, and R. D. Etcheverry, "High Sensitivity Millimeter-Wave Measurement Apparatus," U.S. Patent No. 4510622, 9 April 1985.

46. D. E. Foreman and D. F. Sedivec, "Experimental Observation of the Creeping-Wave Phenomenon in Backscattering Using a Short-Pulse Radar System," Proc. IEEE, 53, pp. 1102-1104, August 1965.

47. R. D. Tompkins, Radar in the Wake of WARC," IEEE Trans. Communications, COM-19, pp. 1170-1176, August 1981.

48. A. W. Rihaczek, Principles of High Resolution Radar, McGraw Hill, 1969.

49. D. L. Mensa, High Resolution Radar Imaging, ARtech, 1981.

50. R. B. Dybdal, K. H. Hurlbut, and T. T. Mori, "High Resolution Instrumentation Radar," accepted for publication, IEEE Trans. Instrumentation and Measurement, March 1987. For circuitry, see also Aerospace Corp. Tech. Rept. TR-0086(6925-05)-3.

51. L. A. Hoffman, K. H. Hurlbut, D. E. Kind, and H. J. Wintroub, "A 94-GHz Radar for Space Object Identification," IEEE Trans. Microwave Theory and Techniques, MTT-17, pp. 1145-1149, December 1969.

52. D. L. Mensa, "Wideband Radar Cross Section Diagnostic Measurements," IEEE Trans. Instrumentation and Measurement, IM-33, pp. 206-214, September 1984.

53. S. Silver, Microwave Antenna Theory and Design, McGraw-Hill, 1949, p. 187.

54. P. M. Woodward, Probability and Information Theory with Applications to Radar, McGraw-Hill, 1953.

55. P. Swerling, "Parameter Estimation Accuracy Formulas," IEEE Trans. Information Theory, IT-10, pp. 302-314, October 1964.

56. D. K. Barton and H. R. Ward, Handbook of Radar Measurement, Prentice-Hall, 1969.

57. R. B. Dybdal and R. H. Ott, "Coherent RF Error Statistics," 1986 IEEE Microwave Theory and Techniques Symposium, Baltimore, MD, 2-4 June 1986. Expanded version accepted for publication IEEE Trans. Microwave Theory and Techniques, pp. 677-680 December 1986. For applications, see also Aerospace Corp. Tech. Rept. TR-0086(6925-05)-1 in publication.

LABORATORY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security projects, specializing in advanced military space systems. Providing research support, the corporation's Laboratory Operations conducts experimental and theoretical investigations that focus on the application of scientific and technical advances to such systems. Vital to the success of these investigations is the technical staff's wide-ranging expertise and its ability to stay current with new developments. This expertise is enhanced by a research program aimed at dealing with the many problems associated with rapidly evolving space systems. Contributing their capabilities to the research effort are these individual laboratories:

Aerophysics Laboratory: Launch vehicle and reentry fluid mechanics, heat transfer and flight dynamics; chemical and electric propulsion, propellant chemistry, chemical dynamics, environmental chemistry, trace detection; spacecraft structural mechanics, contamination, thermal and structural control; high temperature thermomechanics, gas kinetics and radiation; cw and pulsed chemical and excimer laser development including chemical kinetics, spectroscopy, optical resonators, beam control, atmospheric propagation, laser effects and countermeasures.

Chemistry and Physics Laboratory: Atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes, sensor out-of-field-of-view rejection, applied laser spectroscopy, laser chemistry, laser optoelectronics, solar cell physics, battery electrochemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, thermionic emission, photo-sensitive materials and detectors, atomic frequency standards, and environmental chemistry.

Computer Science Laboratory: Program verification, program translation, performance-sensitive system design, distributed architectures for spaceborne computers, fault-tolerant computer systems, artificial intelligence, micro-electronics applications, communication protocols, and computer security.

Electronics Research Laboratory: Microelectronics, solid-state device physics, compound semiconductors, radiation hardening; electro-optics, quantum electronics, solid-state lasers, optical propagation and communications; microwave semiconductor devices, microwave/millimeter wave measurements, diagnostics and radiometry, microwave/millimeter wave thermionic devices; atomic time and frequency standards; antennas, rf systems, electromagnetic propagation phenomena, space communication systems.

Materials Sciences Laboratory: Development of new materials: metals, alloys, ceramics, polymers and their composites, and new forms of carbon; non-destructive evaluation, component failure analysis and reliability; fracture mechanics and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures as well as in space and enemy-induced environments.

Space Sciences Laboratory: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; effects of solar activity, magnetic storms and nuclear explosions on the earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation.